A STABILIZED SOIL ROAD IN VIRGINIA

The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

In This Issue

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STABILIZED SOIL ROADS

BY THE DIVISION OF TESTS, BUREAU OF PUBLIC ROADS

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SOILS are unstable when the force required to displace them laterally under load exceeds their shear strength. Sliding of the soil particles follows. Failure of fills caused by slips, penetration of subgrade soil into the interstices of porous base courses, and the rutting of subgrades, base courses, and road surfaces are the results.

The purpose of soil stabilization is to provide road soils with enough abrasive resistance and shear strength to accommodate traffic under prevalent weather conditions, without detrimental deformation.

There are two general methods for accomplishing this.

1. By providing the soil with coarse and fine materials of the proportions and character required to produce stability, and possibly supplementing this by adding chemical admixtures to maintain the stability thus produced.

2. By incorporating water-insoluble binders in fine-grained or poorly graded soils, consolidating in a particular manner to provide structural stability, and covering the bases thus produced with thin wearing courses to furnish resistance to abrasion.

In either case the stability that can be obtained depends upon (1) the physical characteristics of the soil particles, (2) the cohesiveness of the binder, and (3) the strength and permanency of the joint that can be developed between soil particles and binder.

Methods of determining the properties of the various rock and soil materials used as aggregate, and such binders as bituminous materials and portland cement, have long been used as standard laboratory practice by the engineer.

ADSORPTION BY SOIL PARTICLES IMPORTANT FACTOR IN SOIL PHYSICS

With the development of information on soil stabilization, it has become more and more obvious that the adhesion that can be developed between aggregate and binder plays just as important a part in the performance of the resulting road surface, base course, or stabilized subgrade as the individual properties of binder and aggregate separately.

In such studies as well as those that may furnish a rational explanation of how water alone or water supplemented with chemicals effect soil stabilization, the engineer has had to enlarge his field of study to include investigations of the electrochemical phenomena of adsorption and base exchange long recognized in both agriculture and ceramics.

Adsorption, according to Bancroft (2)[1], is the phenomenon that causes all solids to tend to adsorb or condense on their surfaces any gases or vapors with which they are in contact. When adsorption involves reactions that are essentially chemical or ionic in character, it is termed base exchange. These phenomenon depend upon electrical attractions which may be illustrated as follows:

A piece of iron is attracted strongly enough by a magnet to cling to it and be lifted against the force of gravity. A piece of copper, in contrast, is not so attracted by the magnet. If the two metals were combined in varying proportions the magnet would be expected to attract the resulting alloys in varying degrees covering the whole range from none for the copper to a maximum for the iron.

Similarly all solids attract with varying intensity any gases, vapors, or even solids with which they are in contact. In the air solids adsorb films of air and, in saturated soils, the solids are covered with minute films of moisture. For a liquid to wet a solid in air, the liquid must displace the air film, and for this to occur the solid must attract the liquid more strongly than it attracts the air. Also, only materials that have greater affinity for air than for water can be thoroughly dried. Air is often adsorbed on soil solids so strongly after a period of drought that drops of rain will roll along on dust without wetting it.

Clay adsorbs different liquids to different extent, i. e., its power of adsorption is selective and under suitable conditions one liquid will displace another in contact with the clay. For this reason, a greasy dish is readily cleaned by rubbing it with wet clay, and grease may be removed from wool and cloth by rubbing it with dry clay. This use of dry clay is important industrially in filling cloth.

The power that plastic clays possess of retaining their plasticity when mixed with sand or other nonplastic material is caused by the adsorption of one solid by another. The clay is not distributed uniformly through the pores or interstices of the coarser particles but most of it forms a coating on the nonplastic material and many of the pores remain unoccupied even though there is more than sufficient clay to fill them.

BASE EXCHANGE DISCUSSED

A colloid that holds hydrogen adsorbed on its surface is termed a hydrogen-ionized or H-colloid. One with calcium adsorbed on its surface is termed a calcium-ionized or Ca-colloid. If a substance like hydrated lime $Ca(OH)_2$ is leached through soil containing H-colloids, the calcium replaces the hydrogen to form Ca-colloids and the hydrogen thus released combines with the released $(OH)_2$ to form water. The line of demarcation between selective adsorption and base exchange is often vague.

According to Searle (28) the theory of base exchange was first advanced in 1850. At this time and also in 1852, J. T. Way (35) reported that "* * * soils are able to remove ammonia from its solution, a fact appearing still more extraordinary inasmuch as there is no ordinary combination of ammonia in a state of insolubility in the soil." The removal of ammonia resulted from its replacing lime in the clay, the lime passing into solution. In 1858 Eichorn (9) showed that natural hydrated double silicates, known as zeolites and used largely as water softeners, have this property of exchanging one base for another.

In 1912 Weigner (36) showed definitely that base exchange of silica gel has all the characteristics of an exchange adsorption process. The amount of cations adsorbed is mathematically related to the concentration of the surrounding solutions at equilibrium.

Turner (34) working with tropical soils was able to evaluate the exchange capacities both of the organic matter and of the clay. Bradfield (4), in 1923, supplied information on the types of acids that occur in soils. Arrhenius (1), in 1926, found that the adsorption of dyes by clay is related to their molecular weights, the materials having the higher molecular weights being adsorbed to the greater extent.

Work by Dr. Hans Winterkorn and Dr. L. D. Baver (3, 39) has done much to substantiate and supplement the findings of the earlier investigators on the effects of the chemical characteristics of the soil upon its physical properties.

The performance of the soil mass is so largely dependent upon the character of the contained moisture that the subject of soil physics almost completely resolves itself into a study of the physical properties of soil moisture.

Water may be of two kinds—adsorbed or free—as concerns its adhesion to soil particles. It may be gravitational, capillary, cohesive, or solidified, depending on the performance of the water or the properties it imparts to the soil mass.

In colloidal suspensions, the soil particle may be considered as being encased in a film of electrically adsorbed water, or water of hydration, and suspended in a body of free water as illustrated in figure 1.

Free water has the freezing point, the boiling point, the surface tension, and the viscosity of ordinary water. Adsorbed films, in contrast, have higher boiling points, lower freezing points, greater surface tension, and are more viscous than free water.

It may be considered that the properties of the outermost layer of adsorbed films of water are more nearly like those of free water, and that the properties of the innermost layer are more nearly like those of solidified water or ice. Within the thickness of the film all the properties from those of free water to those of ice would then be represented.

The extent to which the free water and film water influence the performance of soils depends upon both the moisture content of the soil and the surface area of the soil particles. The lower the moisture content at equal grain size and the finer the soil at equal moisture content, the greater will be the influence of the adsorbed water.

Gravitational water is free water drawn into soils by gravity during rains and thaws. Capillary moisture is free water drawn up through the pores of a soil above the water table by capillary force. When the film or skin covering the surface of water is penetrated by an object such as a glass tube having greater attraction for water than for air, a water film proceeds upward and wets the tube above the surface of the liquid. The adjacent water covering, which is part of the adhesive film, is pulled upward until the weight of water in the meniscus thus formed equals the tensile strength of the film.

Bigelow and Hunter, who, according to Meinzer (22), were apparently the first investigators to make direct measurements of the capillary rise in tubes other than glass, concluded that the capillary ascension of water is different in tubes of different substances and that it is
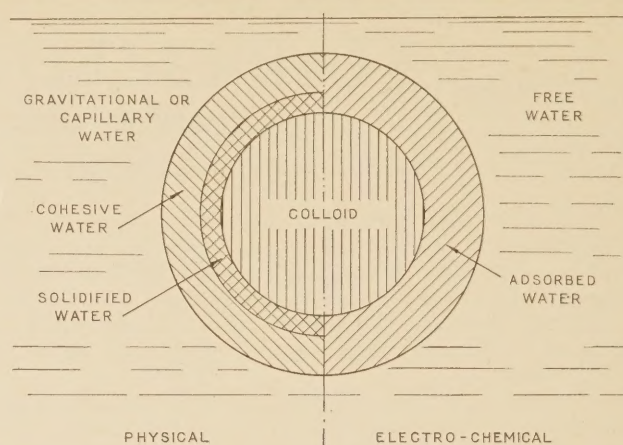
FIGURE 1.—COLLOID ENCASED IN FILM OF ADSORBED WATER AND SUSPENDED IN FREE WATER.

probably a "* * * measure of the adhesion between the liquid and the substance in the wall."

For equal pore size, the greater the adhesive attraction the higher will be the capillary rise, the maximum height being limited by the surface tension of water. For equal adhesive attraction, the height of capillary rise and the corresponding adhesion of the films increases as the diameters of the pores decrease.

SOLIDIFIED WATER FILMS CAUSE PLASTIC SOILS TO FORM HARD CLODS

To illustrate how changes in the properties of water affect the performance of soils, assume that a small amount of soil is shaken up thoroughly in water so that the soil particles are dispersed throughout the water. If the resulting soil suspension is set aside, the soil particles will gradually settle to the bottom and form a sediment. The porosity, or moisture content, of this sediment at first is so high that the sediment has all the properties of a fluid, i. e., due to its own weight it will deform and acquire the shape of any vessel in which it is placed, and it has buoyant properties such that its density may be measured with a hydrometer. At this consistency the soil has a high moisture content and, in turn, the ratio of free water to adhesive water is great, so that the performance of the mixture is dominated by properties of free water.

As the moisture content of the soil is reduced the consistency becomes that of slips and slurries which also deform under their own weight to assume the shape of any vessel in which they are placed. However, the soil no longer has the buoyancy of a fluid and its density can no longer be determined with a hydrometer. At this consistency, the soil can be said to be in the viscous state. The minimum moisture content of the soil in this state is the true lower liquid limit of the soil, although the test constant, the liquid limit as determined by the Atterberg test and discussed below, is somewhat less.

When the moisture content is reduced below the true lower liquid limit, the consistency of plastic soils is so changed that they become pastes that require the application of external pressure in order to undergo change in shape. The ratio of lubricating to adhesive moisture, while decreasing, is still sufficiently great to cause the properties of the soil to be dominated by the lubricating water.

Upon further reduction of moisture, a moisture content is reached at which the properties of the soil are

altered abruptly from those of a plastic paste to those of a semirigid material with a correspondingly abrupt and considerable increase in its bearing value. This results from the fact that the ratio of lubricating to adhesive moisture becomes so reduced that the adhesive water abruptly becomes the dominating influence on the performance of the soil. This moisture content is the plastic limit of the soil.

On continued evaporation, the soil acquires a maximum density due to this evaporation. The moisture content at this density is the shrinkage limit of the soil. Further reduction of moisture below the shrinkage limit is not accompanied by further reduction in volume. Continued evaporation below the shrinkage limit causes the mobile moisture to recede in the pores leaving only the very thin, more or less solid films, which may have thicknesses of only a few millionths of an inch.

When all of the pore moisture is finally evaporated, the adhesive films are reduced to a solidified state with molecular thicknesses. Such films are really ice since at the enormous pressures (estimated greater than 20,000 atmospheres) under which they exist the melting point of ice is, according to the Smithsonian physical tables (29), in excess of 76° C. or 168° F. It is because of these solidified water films that thoroughly dried plastic soils form cakes and clods instead of dust.

Means of providing a strong and lasting joint between soil particles and the adhesive films connecting them include the use of admixtures and compaction.

NUMEROUS ADMIXTURES USED IN SOIL STABILIZATION

The kinds of admixtures and the means by which they effect soil stabilization are summarized as follows:

1. Mineral aggregates and soil constituents of the character and sizes required to make graded mixtures stable.

2. Moisture-retentive chemicals, such as calcium chloride and common salt, to provide soil binders with enough moisture to facilitate the compaction of graded mixtures by traffic.

3. Solutions of electrolytes, such as calcium chloride, common salt, sodium hyposulphite, etc., to reduce the thickness of adhesive water films on soil particles and thus provide stabilized mixtures with greater density.

4. Primes and fillers such as soaps, stone dust, and slag to increase the adhesion between mineral constituents and the chemical and bituminous admixtures and thus assist in retaining the benefits the admixtures were expected to furnish.

5. Neutralizers such as limestone dust, slag, hydrated lime, etc., that serve to alkalize acid soils and thus prevent the loss of stabilizing chemicals caused by detrimental base exchange.

6. Water-insoluble binders, such as portland cement and bituminous materials, to furnish films more substantial than those of moisture alone and to destroy permanently the colloidal properties responsible for detrimental volume change in soil mixtures.

The effect of admixtures on the density of stabilized soil may be illustrated by means of tests devised by R. R. Proctor (25). They are based on the fact that for each soil there is but one moisture content, termed the "optimum" moisture content, at which the maximum density is produced by a specific amount of compacting. For each density, each soil has a particular stability as indicated by the force required to penetrate the soil with a footing of known area at a given speed. When the soil is compacted to maximum den-
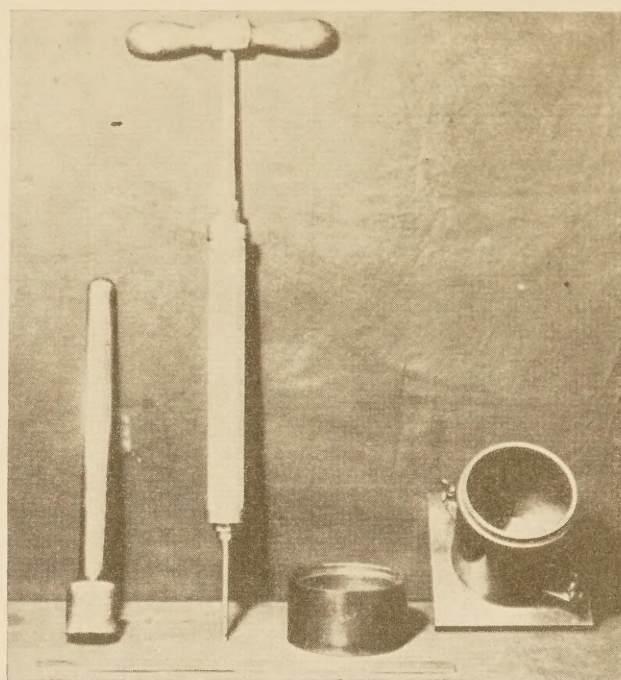
FIGURE 2.—UPPER; THE PROCTOR COMPACTION TEST APPARATUS. LOWER; MEASURING THE STABILITY OF A SAMPLE IN THE FIELD.

sity at optimum moisture content, the adsorptive attraction between water and soil particles is probably such that the tendency for moisture to enter the soil and expand or soften the soil mass is largely eliminated.

The apparatus required for the compaction test consists of a brass cylinder 4 inches in diameter and about 4½ inches deep, which is mounted on a removable base plate and fitted with a detachable collar 2 inches high to hold the loose soil in place while compacting; a 5½-pound cylindrical rammer with an end area of about 3 square inches; and a plasticity needle of known end area. (See fig. 2.)

In the compaction test approximately 5 pounds of dry soil passing the no. 10 sieve are mixed thoroughly with just enough water to make it slightly damp and compacted in the cylinder in 3 layers, each layer receiving 25 blows from the rammer dropped a distance
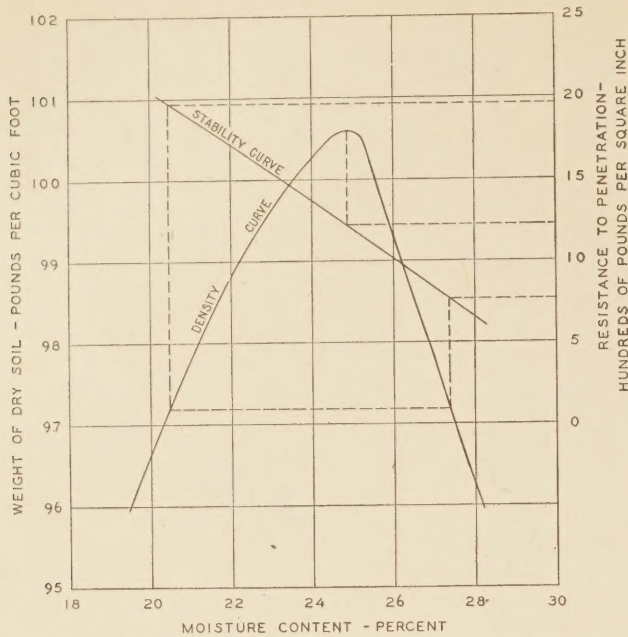
FIGURE 3.—EFFECT OF VARIATIONS IN MOISTURE CONTENT UPON THE DENSITY AND STABILITY OF A SOIL.

of 1 foot. The soil is then struck off to the level of the cylinder, weighed, and the stability determined with the plasticity needle by measuring the force required to force it into the soil at the rate of one-half inch per second. A small sample of the compacted soil is oven dried to determine the moisture content.

This procedure is repeated, each time adding about 1 percent more water, until the soil becomes very wet and there is a substantial decrease in the weight of the compacted wet soil. The effect of moisture on the densities of the compacted samples is shown by plotting the densities of the compacted soil when dry, expressed in pounds per cubic foot, against moisture content. The plasticity needle readings, expressed in pounds per square inch, are also plotted against moisture content to show the effect of moisture on stability.

Two curves resulting from the test (fig. 3) illustrate the significance of the compaction data. The dry-weight, moisture-content curve discloses that for this soil a moisture content of about 25 percent is required if maximum compaction is to be obtained. The corresponding stability is about 1,200 pounds per square inch.

If, at a specified density, the stability of this particular soil as indicated by the plasticity needle is higher than 1,200 pounds, the increase can be considered as only temporary if the soil is to be unprotected from water after construction. For this soil a stability of 1,950 pounds per square inch indicates a moisture content of slightly more than 20 percent. This corresponds to a dry weight of about 97 pounds per cubic foot. This density is representative also of a moisture content of slightly more than 27 percent which, in turn, corresponds to a stability of but 750 pounds per square inch.

TEMPERATURE IS A FACTOR TO BE CONSIDERED IN COMPACTING SOILS TO HIGH DENSITY

It is proverbial that molasses is "slower" in January than in June. The same can be said about water for it also is more viscous in cold weather. Because of

this, sedimentation proceeds at a slower rate in cold water, the films of adsorbed water on soil particles are thicker, for equal degrees of compaction the moisture content of soil is greater, and for equal moisture contents the stability of soil is greater during periods of low temperature.

It can be shown by the application of Stokes' law that the times required for settlement through a depth of 20 feet of water at temperatures of about 100° F. and 35° F. would be respectively as follows: Coarse sand grains with diameters of 1.0 millimeter, 4.6 seconds and 11.4 seconds; silt grains with diameters of 0.01 millimeter, 12.8 hours and 31.6 hours; and clay particles with diameters of 0.001 millimeter, 53 days and 132 days. In these computations, only the increase in the viscosity of free water caused by the drop in temperature is considered.

The greater thickness of the adsorbed films is indicated by data furnished by Baver and Winterkorn (3) and shown in table 1. Here, the cubic centimeters of adsorbed films or hydration per gram of colloid is greater at low than at higher temperatures. Thus the Putnam colloids ionized with sodium have 5.25 cubic centimeters of adsorbed water film per gram at 30° C. and but 2.52 cubic centimeters at 99° C.

TABLE 1.—*Hydration* [1] *of Putnam and Wabash colloids as affected by temperature*

PUTNAM COLLOID			
Temperature	Hydration in cubic centimeters of water per gram of colloid ionized with—		
	Sodium	Calcium	Hydrogen
°C.	Cm³ per gram	Cm³ per gram	Cm³ per gram
30	5. 25	9. 75	5. 20
50	4. 56	3. 90	3. 52
70	2. 53	1. 98	2. 16
99	2. 52	. 86	2. 70
WABASH COLLOID			
30	7. 45	6. 74	17. 95
50	6. 29	6. 14	16. 08
70	5. 09	6. 44	14. 79
99	3. 67	7. 10	9. 70

[1] From viscosities.

The effects of temperature on the moisture contents, densities, and stabilities of soils compacted in the same manner are indicated by the curves shown in figures 4 and 5. The gradings and the physical properties of the soils used in the compaction tests discussed below are given in table 2.

The red clay and Iredell soils are representative of the clay soils conspicuous because of their high plasticity and volume change. The Arlington soil is a typical silt-loam soil. The Manor soil is a silty soil that contains enough mica flakes to cause the soil to be highly elastic.

Soil designations, such as Iredell, Manor, Putnam, and Cecil, used in this report are names given to particular series of soils formed under given conditions of weathering. The names generally indicate the locality (township or county) in which a particular series was first identified and mapped. Thus the Manor series is representative of a type first mapped in Manor Township, Lancaster County, Pa. The names are used here
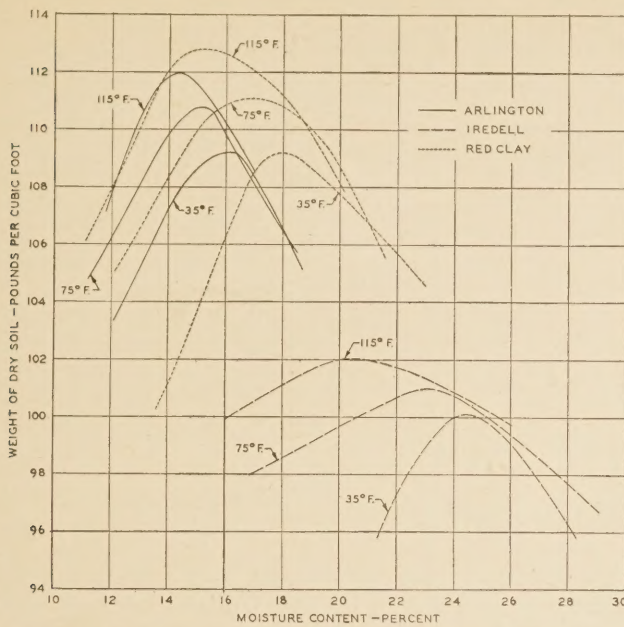
FIGURE 4.—EFFECT OF TEMPERATURE UPON THE DENSITY OF DIFFERENT SOILS.

FIGURE 5.—EFFECT OF TEMPERATURE UPON THE STABILITY OF DIFFERENT SOILS.
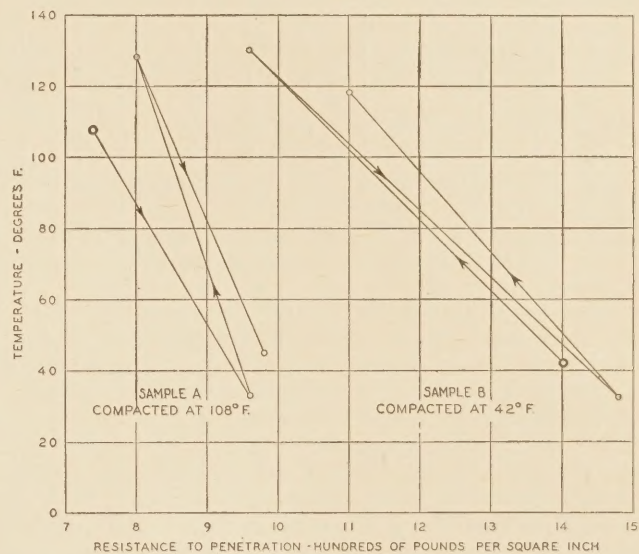
FIGURE 6.—EFFECT OF ALTERNATIONS OF HIGH AND LOW TEMPERATURE ON THE STABILITY OF RED CLAY SOIL.

solely for the purpose of identification and not to denote physical characteristics.

In figure 4 are shown the dry-weight, moisture-content curves produced by equal amounts of compacting for three different soils as determined at three different temperatures. In all cases the maximum densities are higher and the optimum moisture contents lower, the higher the temperature at the time of test.

TABLE 2.—*Results of tests on different soils*

MECHANICAL ANALYSIS [1]

Soil	Particles larger than 2.0 mm	Particles smaller than 2 mm (percent by weight)					
		Coarse sand 2.0 to 0.25 mm	Fine sand 0.25 to 0.05 mm	Silt 0.05 to 0.005 mm	Clay smaller than 0.005 mm	Colloids smaller than 0.001 mm	Passing no. 40 sieve
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Red clay_____	0	4	8	20	68	51	98
Iredell_____	0	14	8	20	58	42	89
Arlington_____	0	6	27	36	31	22	99
Manor_____	0	7	42	39	12	8	98

PHYSICAL CHARACTERISTICS [1] OF MATERIAL PASSING NO. 40 SIEVE

Soil	Liquid limit	Plasticity index	Shrinkage		Moisture equivalent	
			Limit	Ratio	Centrifuge	Field
Red clay_____	65	47	10	2.0	31	25
Iredell_____	78	55	12	2.0	[2] 76	40
Arlington_____	27	7	19	1.7	33	21
Manor_____	37	11	38	1.4	22	42

[1] Determined in accordance with standard A. A. S. H. O. and A. S. T. M. testing procedures.
[2] Waterlogged.

Figure 5 shows the relations between the stability as measured by the plasticity needle and the temperature of the sample. Each curve is for a single sample compacted at high temperature and shows that an increase in stability occurred when the temperature was reduced, the moisture content and density remaining constant.

The sample of Iredell clay was compacted at a temperature of 125° F. and a moisture content of 24.6 percent (the optimum moisture content for a temperature of 35° F.). The temperature of the sample was then reduced first to 68° F. and then to 32° F. The stabilities were 800 pounds per square inch at 125° F., 1,000 pounds per square inch at 68° F., and 1,240 pounds per square inch at 32° F.

The stabilities of the other two samples (fig. 5), likewise were greater at the lower temperatures. The Arlington soil had a stability of 710 pounds per square inch at 42° F. as compared with 340 pounds per square inch at 115° F. For the red clay the stability was 2,000 pounds per square inch at 32° F. as compared with 1,400 pounds per square inch at 125° F.

The curves in figure 6 show that the phenomenon of change in stability with change in temperature is a reversible one, the stability increasing with lowering temperatures and decreasing with rising temperatures. In figure 6 the curve marked A shows the effect of compacting a sample at high temperature and then successively lowering and raising the temperature. The curve marked B shows the effect of compacting the sample at a low temperature and then successively increasing and decreasing the temperature. The sam-
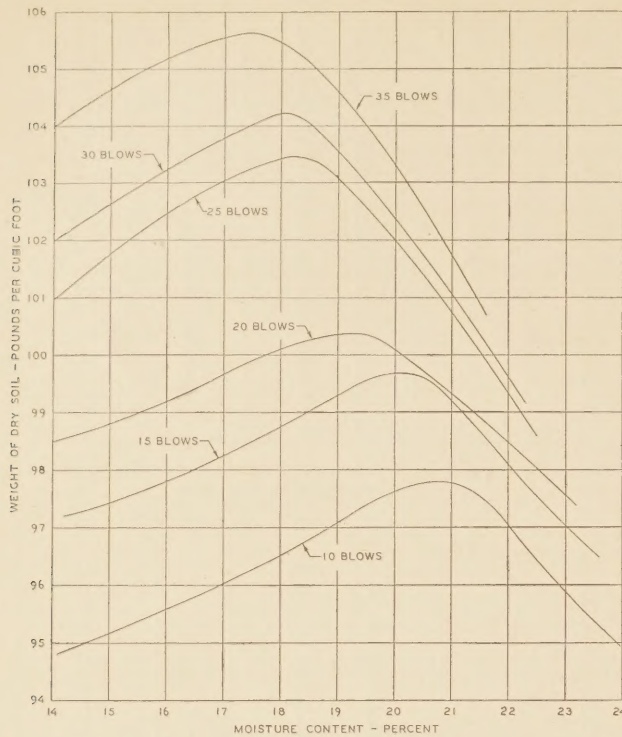
FIGURE 7.—EFFECT OF AMOUNT OF COMPACTING UPON THE DENSITY OF MANOR SOIL.

FIGURE 8.—EFFECT OF AMOUNT OF COMPACTING UPON THE DENSITY OF MANOR SOIL AT OPTIMUM MOISTURE CONTENTS.

ples used in obtaining the information shown in figure 6 were not compacted at the optimum moisture content, and the moisture contents were not the same for samples A and B. This explains the differences in stability shown by the two curves.

Decrease in the temperature at constant moisture content causes a decrease in the free water and a corresponding increase in the adsorbed water. This decrease in the ratio of the lubricating to the adhesive moisture results in an increase in the relative viscosity of the total moisture, adsorbed and free. This increase is in addition to the increase in the viscosity of the free water caused by drop in temperature. The total variation in the viscosity of all contained moisture can be considered as the primary influence on the variation in density and stability with variation in the temperature of compacted soils.

The dry-weight, moisture-content curves in figure 7 show the effect of the amount of compacting the sample received upon its density. The curves show the results of varying the number of blows per layer in compaction tests of the Manor soil. The greater the number of blows per layer, the lower were the optimum moisture contents and the higher were the maximum densities of the compacted samples. Figure 8 shows the relation between the dry weights at optimum moisture contents and the number of blows per layer for the Manor soil.

PROPER GRADING OF MIXTURE IS A FIRST CONSIDERATION IN CONSTRUCTING STABLE SOIL ROADS

According to Dr. C. M. Strahan (*30*) the best graded soil mixtures can be expected to furnish roads that, when dry, are strong, hard, free from noticeable ruts, holes, or corrugations, possess a well-shaped crown, and drain freely into the side ditches. A thin layer of loose,
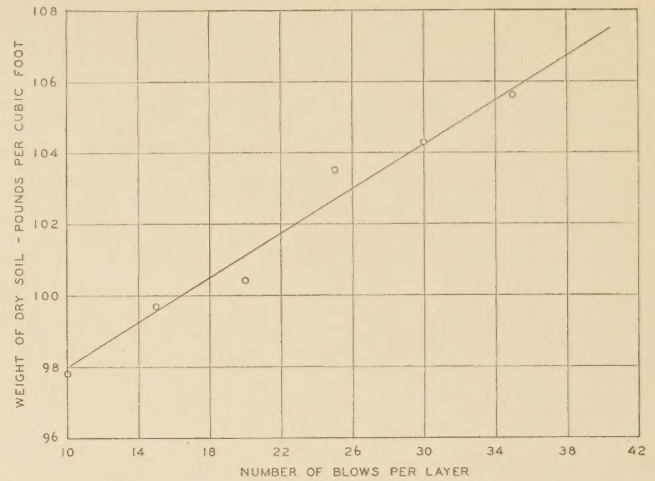
sandy material may sometimes be present, but not sufficient in amount to impede traffic. During heavy rains or after long wet spells the surface should not be noticeably softened, but should remain practically non-slippery and free from appreciable mud. Driving speed may need to be only slightly reduced.

Proportioning of soil materials for surface courses should provide:

1. Enough crushed rock, gravel, or slag retained on the no. 10 sieve to furnish the strength and hardness needed to resist the abrasive action of traffic.

2. Enough sand or other granular material passing the no. 10 sieve and retained on the no. 200 sieve to provide the interlocking of soil grains and thus increase the shear strength.

3. A quantity of silt and sand (particles 0.074 to 0.005 millimeters in diameter) to act as a filler and to provide the capillary bond necessary for stability when the binder clay loses cohesion in wet weather.

4. Enough clay (particles smaller than 0.005 millimeters in diameter) to retain the minute adhesive films after the larger films of capillary moisture have evaporated and thus provide the adhesion required to maintain stability during dry weather.

The abrasive resistance and the degree of interlocking of soil mixtures are indicated by the grading of the granular fractions. Materials falling within the following limits, by weight, satisfy the above requirements and should produce good surfacing layers:

Passing:	*Percent*
1-inch sieve	100
¾-inch sieve	85–100
No. 4 sieve	55–85
No. 10 sieve	40–65
No. 40 sieve	25–50
No. 200 sieve [1]	10–25

[1] The smallest fraction of the grading determination referred to in previous reports was that passing the no. 270 sieve. The hydrometer method of analysis has been used to determine the fraction referred to as that passing the no. 270 sieve because that method is more practical than one using the no. 270 sieve. However, the use of the no. 200 sieve is practical. Furthermore, it has been found that a knowledge of the characteristics of the fraction passing the no. 200 sieve serves our purpose as well as a knowlege of the characteristics of the fraction passing the finer sieve and eliminates the necessity of making the hydrometer analysis. This explains the substitution of the no. 200 for the no. 270 sieve in the grading requirements.

Material larger than 1 inch can be used under certain conditions but the amount should not exceed 10 percent. Also the maximum size should never exceed one-third the thickness of the stabilized layer. The
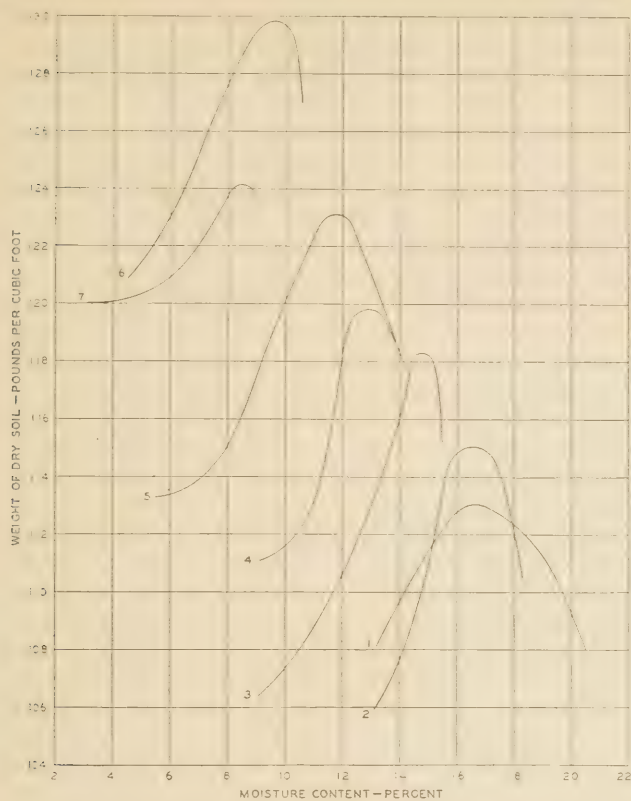
FIGURE 9.—EFFECT OF GRADING OF SAMPLES ON THE RELATIONS BETWEEN DENSITY AND MOISTURE CONTENT.

fraction passing the no. 200 sieve should be less than two-thirds of the fraction passing the no. 40 sieve.

For base courses the fraction passing the no. 200 sieve should be within the range of 0 to 25 percent and should be less than one-half of the fraction passing the no. 40 sieve.

The dry-weight, moisture-content curve for a soil passing the no. 10 sieve and meeting the requirements for a good soil mortar is shown in figure 9, sample 6. The grain size accumulation curve for this sample is shown in figure 10.

The effects of increasing the percentages of silt and clay are also shown in these figures. The data are summarized in table 3.

TABLE 3.—*Grading, optimum moisture contents, and densities of samples*

Sample number	Mechanical analysis								Optimum moisture content	Dry weight at optimum moisture content
	Passing no. 10, retained on no. 20	Passing no. 20, retained on no. 40	Passing no. 40, retained on no. 60	Passing no. 60, retained on no. 100	Passing no. 100, retained on no. 140	Passing no. 140, retained on no. 270	Silt	Clay		
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Lb. per cu. ft.
1	1	1	2	4	2	2	20	68	16.7	113.0
2	0	1	1	2	1	2	60	34	16.5	115.0
3	0	1	0	2	14	22	37	21	14.7	118.3
4	0	1	0	22	11	19	30	17	12.9	119.8
5	0	0	22	18	23	15	23	13	11.8	123.1
6	24	16	13	10	5	9	15	8	9.6	129.8
7	28	18	14	6	6	10	13	0	8.5	124.1
8	24	16	14	10	6	7	5	18	8.9	129.3
9	0	25	20	15	7	10	5	18	10.4	126.9
10	0	0	29	23	12	13	5	18	11.8	123.8
11	0	0	1	36	18	22	5	18	12.8	120.4
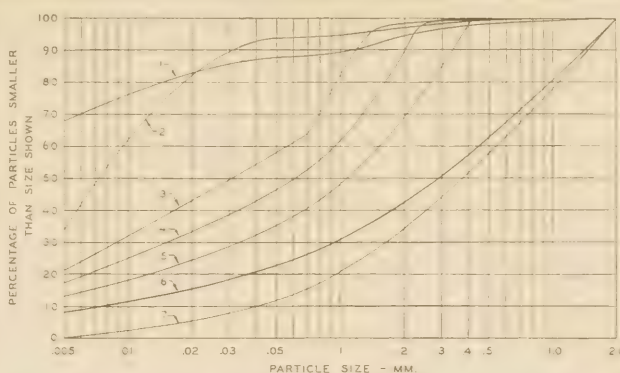
FIGURE 10.—GRAIN SIZE ACCUMULATION CURVES OF SAND ADMIXTURES.

The red clay, sample 1, contains 68 percent clay, 20 percent silt, and 12 percent sand. At the optimum moisture content of 16.7 percent the dry weight was 113.0 pounds per cubic foot as compared with a dry weight of 129.8 pounds at 9.6 percent optimum moisture content for the excellent soil mortar (group A–1 soil), sample 6.

Samples 2, 3, 4, and 5 were obtained by adding silt and sand to the red clay represented by sample 1. An attempt was made to obtain proportions representative of the different fractions of sample 6. Thus sample 5 represents approximately the grading of the fraction of sample 6 material that passes the no. 40 sieve; sample 4 represents the fraction that passes the no. 60 sieve; sample 3 represents the fraction that passes the no. 100 sieve; and sample 2 represents the fraction that passes the no. 270 sieve.

Figure 9 shows that as the total sand is decreased from that of sample 6 to that of sample 2 the density of the compacted mixtures decreases and the optimum moisture contents increase. In sample 7 an attempt was made to approximate the grading of the fraction of sample 6 that was larger than 0.005 millimeter. As would be expected in the absence of the clay fraction the optimum moisture content is smaller than that of sample 6, being only 8.5 percent. The maximum density, however, is but 124.1 pounds per cubic foot, which is 5.7 pounds per cubic foot less than that of the excellently graded material (sample 6).

In figures 11 and 12, data for sample 6 are compared with similar data for four samples in which the sand, silt, and clay fractions are constant but the grading of the sand fraction is varied. The maximum density of sample 8 with 5 percent silt and 18 percent clay and approximately the same sand gradation as sample 6 is slightly lower than that of sample 6. As the coarser sand fractions are eliminated from samples 9, 10, and 11 and the mixtures approach a more nearly uniform grain size, their densities decrease.

PHYSICAL AND CHEMICAL PROPERTIES OF AGGREGATE AND BINDERS MUST BE CONSIDERED

The aggregate of satisfactory stabilized mixtures should be hard and durable enough to resist weathering, traffic abrasion, and crushing. Sound, tough particles or fragments of gravel, stone, slag, or combinations of them, crushed to the proper size, should prove suitable. Certain types of shales and similar materials that break up and weather rapidly when alternately frozen and thawed, or wetted and dried, should not be used.
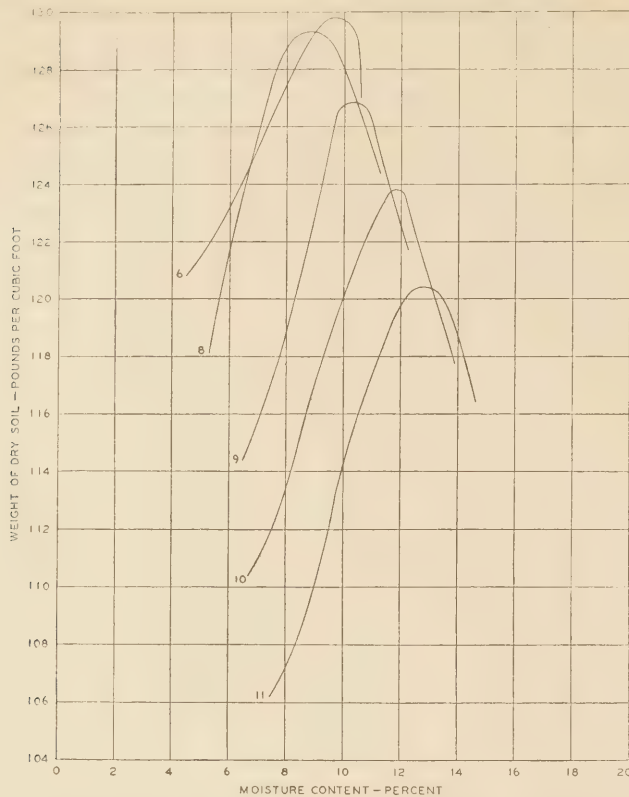
FIGURE 11.—EFFECT OF GRADING OF SAMPLES ON THE RELATIONS BETWEEN DENSITY AND MOISTURE CONTENT.

FIGURE 12.—GRAIN SIZE ACCUMULATION CURVES OF SAND ADMIXTURES.

FIGURE 13.—RELATION BETWEEN MOISTURE CONTENT AND DEFORMATION FOR A SOIL SAMPLE UNDER CONSTANT LOAD.

The soil fines should be of a character such as to provide graded mixtures with the proper balance of capillarity and cohesion without risk of detrimental volume change. Fines which swell enough in the presence of moisture to have moisture contents appreciably in excess of their plastic limits are likely to prove the least desirable. This is because the more the moisture content increases above the plastic limit, the more likely is clay to become a lubricant instead of a binder.

Just as the adhesive water instead of the free water becomes the determining influence when the moisture content of a soil is reduced from above to below the plastic limit, there is a corresponding opposite change when the moisture content of clays is raised from below to above the plastic limit. With this change the clay can be considered as changing from a binding to a lubricating medium as illustrated in figure 13. It will be noted that for a constant load, the deformation increases very slowly (about 0.00026 inch) for each 1 percent increase in moisture content, until a moisture content approximately equal to the plastic limit is reached. The lubricating effect of the moisture above this amount is indicated by the fact that the increase in deformation is thereafter about 100 times as great (0.022 inch) for each 1 percent increase in moisture content (15).

Finally, the surface characteristic of the entire mixture should be such as to provide satisfactory adherence of chemical or bituminous admixtures to the mineral particles and to prevent the occurrence of detrimental base exchange.

In addition to actual swell test data, such qualities as high plasticity, considerable shrinkage on drying, high moisture equivalents, and the like, also indicate soils likely to undergo detrimental volume change.

The more acid the soil, the greater is its base exchange capacity, and consequently its corrosive properties. The relative acidity or alkalinity is disclosed by the concentration of the hydrogen ions.

Of the two parts of hydrogen and one of oxygen (H_2O) that comprise water, one part of the hydrogen (H) may be considered as positive, acid-producing ion; the other part of the hydrogen in combination with the oxygen (OH) may be considered as the negative, alkaline-producing hydroxyl. The pH value, which is used to indicate the concentration of hydrogen ions, equals the reciprocal of the logarithm of the grams of ionized hydrogen per liter of solution or suspension. Thus the total ionized hydrogen in grams per liter equals 10^{-pH}.

When the hydrogen and the hydroxyl are in complete equilibrium, as in distilled water, the pH value equals 7.0. The lower the pH value below 7.0 the greater is the acidity of the liquid. The higher the pH value above 7.0 the greater is the alkalinity of the fluid.

Figure 14 shows the relations between the depth of corrosion of metal pipes and the pH value of the soils in which the pipes are buried (7).

The physical characteristics indicative of swell, the pH values which disclose the relative acidity of soils, and the electrochemical characteristics that control the adhesion between aggregate and binder, depend largely upon both the chemical composition of the soil particles and the ions adsorbed on their surfaces.

In humid, northern climates, weathering may cause the iron and aluminum oxides to be leached from the soil, leaving relatively large accumulations of silica. In a humid tropical climate, in contrast, there is a tendency
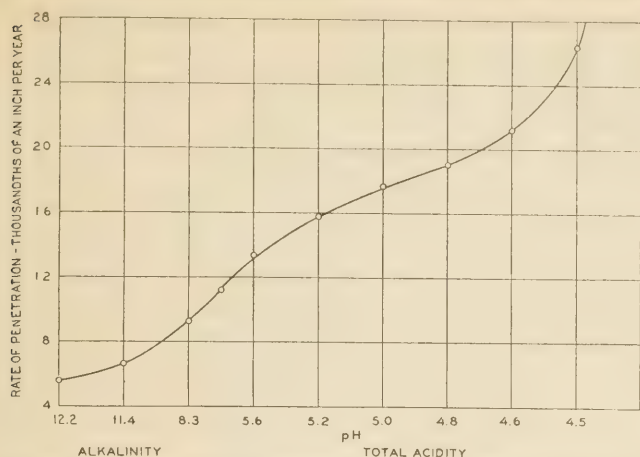
FIGURE 14.—RELATION BETWEEN ACIDITY AND CORROSION OF STEEL IN SYNTHETIC SOIL.

for iron and aluminum compounds to accumulate. The ratio of silica to the combined iron and aluminum oxides is termed the silica sesquioxide ratio and is designated by the symbol "SiO_2/R_2O_3".[2]

Clays high in silica, termed "podsols", are acidic and consist principally of the highly water-adsorbent scale-like particles, that have high plasticity and shrinkage values. Soils high in iron and alumina, termed "laterites", are alkaline and consist more of the bulky or spherical particles.

Russell (27), in summarizing the work of previous investigators, states that the typical clay properties—plasticity, stickiness, power of swelling on moistening and of shrinkage on drying, and power of cementation—all increase as the SiO_2/R_2O_3 ratio increases from 2 to 6 or 7 (podsols) but do not usually appear when the ratio (SiO_2/R_2O_3) is 2 or less (laterites).

The greater swelling of soils with the higher SiO_2/R_2O_3 ratios, as found by Winterkorn and Baver (3), is shown in table 4.

TABLE 4.—*Influence of adsorbed ions on the water affinity of soil colloids*

Type of clay	SiO_2 / R_2O_3	Swelling for ions of—					
		Sodium	Lithium	Potassium	Calcium	Barium	Hydrogen
		Cm³ per gram	*Cm³ per gram*	*Cm³ per gram*	*Cm³ per gram*	*Cm³ per gram*	*Cm³ per gram*
Bentonite	5.0	11.1	10.8	8.6	2.5	2.5	2.2
Putnam	3.2	4.0	5.0	.5	.9	.9	.8
Wabash	3.2	3.7	3.1	.6	.8	.7	.9
Iredell	1.8	.6	.4	.02	.3	.4	.2

ADSORBED IONS AFFECT PERFORMANCE OF SOILS

Research in base exchange by Joseph and Oakley (19) has shown that generally the plasticity and shrinkage were greatest in soils saturated with lithium ions. As the kind of adsorbed ions was changed successively to sodium, magnesium, calcium, potassium, ammonium, and hydrogen ions, the plasticity was gradually reduced.

The shrinkage was gradually reduced as the kind of adsorbed ions was changed successively to sodium, magnesium, calcium, hydrogen, ammonium, and potassium ions. The moisture equivalents were highest for the sodium-ionized clay and were reduced gradually as the kind of adsorbed ions was changed successively to

[2] The symbol SiO_2/R_2O_3 stands for $SiO_2/(Fe_2O_3+Al_2O_3)$.

lithium, magnesium, hydrogen, calcium, and potassium ions.

Joseph (18) gives an example of a sodium clay having a moisture equivalent double that of the calcium clay. The values were as follows: Natural soil, 69 percent by weight; sodium-ionized clay, 125 percent; and calcium-ionized clay, 63 percent.

The effect of adsorbed ions upon the swell and slaking values of clays as found by Dr. Winterkorn (39) is shown in tables 4 and 5.

According to Russell (27), the normal clay of fertile soils is a calcium clay, but the calcium can easily be replaced by other bases or by hydrogen; a new clay then arises. Two of these clays, the acid and the sodium, occur somewhat frequently in nature.

TABLE 5.—*Influence of adsorbed ions on slaking time*

Type of soil	SiO_2 / R_2O_3	Natural soil	Time of slaking for soil having ions of—							
			Magnesium	Hydrogen	Potassium	Iron	Aluminum	Barium	Sodium	Calcium
		Min.	*Min.*	*Min.*	*Min.*	*Min.*	*Min.*	*Min.*	*Min.*	*Min.*
Cecil	1.3	147	209	122	121	93	65	61	24	24
Hagerstown		15	49	26	35	15	20	32	341	23
Putnam	3.2	38	31		24	26			420	26

Additional information on these types of clay is furnished by Taylor (31) as follows:

Since the clay fraction of a soil shows marked flocculation phenomena, it indicates that the clay particles are charged. The present conception is that the charge on the particle is negative, due to the anions of the clay, and surrounding them are the positively charged kations, the hydrogen, calcium, magnesium, potassium, and sodium. It is thus possible to have a series of clay types according to the kations present. The most important clay types are hydrogen clay, characteristic of an acid soil; calcium clay, the normal constituent of agricultural land and of silt carried and deposited in fresh water; and the sodium clay, which is the characteristic clay in salt and alkaline land. From the geological point of view, calcium clay and sodium clay are the most important, as they are characteristic of fresh water and marine conditions respectively. When a silt containing calcium clay is carried in suspension and deposited in water containing sodium chloride, the sediment will contain sodium clay as a characteristic constituent.

Other methods by which sodium clay may be formed are: (a) the submergence of strata in sea water; and (b) by the capillary rise of sodium chloride solutions from a subsoil water table containing this salt in solution. These two latter modes of formation are characteristic of deltaic deposits. It will be seen, therefore, that sodium clay is a characteristic constituent of sediments formed under marine, estuarine, or deltaic conditions, and that calcium clay is only associated with fresh water sediments.

According to Taylor (31), the sodium clay remains flocculated in the presence of sodium chloride and is stable in the presence of an excess of that salt. On replacement of the salt solution with pure water, however, the rate of percolation decreases, the percolate becomes alkaline, and finally the sodium clay becomes impermeable.

Russell (27) states: "Sodium clay easily hydrolyzes * * *. It is very sticky, impervious to air, and dries into hard, large lumps which break down in water to a paste. It is difficult to work."

According to Searle (28), the more highly dispersed the hydrogen or H-clay, the more acid can it be at the optimum silica content.

According to Taylor (31), the properties of calcium clay differ considerably from those of sodium clay.

The hydrolysis of calcium clay is a much slower process and the calcium clay is flocculated in the presence of fresh water. It is neutral, pH value from 6.5 to 8.5, according to the amount of carbonic acid or calcium bicarbonate present, and holds more water in the air-dry condition than under wet conditions. It is less sticky, more permeable and therefore drains more easily.[3]

NEUTRALIZERS USED TO PREVENT BASE EXCHANGE IN SOILS

The best way to insure that detrimental exchange will not occur is to have the soil mixture alkaline. Limestone dust and granulated slag seem admirably suited for use as pretreatments or with other admixtures to neutralize or "sweeten" acid soils and thus prevent detrimental base exchange.

According to Russell (27) the action of calcium carbonate on the soil is, in principle, very like that of any other salt. The calcium replaces hydrogen or sodium in the clay, thus converting an acid or alkaline clay into the more usual calcium clay; it also replaces acidic hydrogen in humic acid, forming the so-called calcium humate or neutral humus.

Dr. Winterkorn's work (39) furnishes some idea of the amount of neutralizer which may be required through the determination of the exchange capacities for the various types of clays completely ionized with hydrogen. If complete replacement occurred, his data show the grams of replaceable hydrogen per 1,000 grams of colloid to be as follows: Bentonite, 0.95; Putnam clay, 0.65; Wabash clay, 0.78; Iredell clay, 0.35. It is hardly likely that any properly graded road surface would ever contain more than 5 percent of clay colloid as active as the Putnams. If this is true, then in a road surface 4 inches thick compacted to an initial density of 130 pounds per cubic foot, there would be but 19.5 pounds of colloid per square yard of road surface. In such case there would be $0.00065 \times 19.5 = 0.0127$ pounds of replaceable hydrogen.

The amount of neutralizer required to replace completely the hydrogen equals the molecular weight of the neutralizer divided by the valence of its metal times the amount of replaceable hydrogen.

The molecular weight of calcium carbonate ($CaCO_3$) is 100 and calcium has a valence of 2. The amount of calcium carbonate required to replace the 0.0127 pound of hydrogen then becomes $\frac{100}{2} \times 0.0127 = 0.64$ pound.

Dr. Winterkorn's work further suggested that in the absence of leaching, but 26.9 percent of the total available hydrogen would be exchangeable for calcium ions. Under this condition but 0.17 pound of calcium carbonate per square yard of the road surface referred to above would be required. However, inability to control the conditions under which base exchange occurs in road surfaces and bases, in a manner comparable to laboratory control, requires the amount of neutralizer to be considerably in excess of that indicated by the computations.

With highly acid conditions, a maximum of 5 pounds of stone dust or slag per square yard of road surface or base will probably suffice to prevent detrimental base

exchange. A smaller amount of hydrated lime might also produce the desired result.

PRIMES AND FILLERS USED TO INCREASE SOIL STABILITY

Materials that effect a beneficial change in the electrical fields surrounding the surfaces of the mineral constituents may be used to advantage as primes when the natural soils have greater attraction for films of air, water, or natural gels than for those of the admixtures expected to provide stability. Particularly in the stabilization of such materials as the "blow" sands of Nebraska and the beach sands of Florida is it likely that films of natural gels would merit special consideration.

The effect of such primes on soils is similar to that produced by coating a metal with acid before the application of solder, or shellacking the knots before painting lumber.

Winterkorn (38), Reagel, and Schappler [4] have experimented with soap primes as means to increase the adhesion between soils and bituminous materials. The greater adhesion of the oil for the soil provided by the soap pretreatment was demonstrated when a heavy rain washed the oil from a commonly constructed earth-gravel-oil mixture but did not wash it from the soap-treated section. It was indicated also that different soaps may be desirable for different soils.

In 1932, Victor Nicholson (24) called attention to the effect of surface chemistry upon the stability of asphaltic pavements. He described one sheet asphalt pavement in Chicago in which the sand grains on the surface became partly white and bare of asphalt not long after construction, as contrasted with other pavements in which the asphalt adhered so tenaciously that they did not become white. The surface whitening occurred during the first summer after the pavement was laid and was as bad in places where there was no traffic as where automobiles traveled.

In 1927, Mr. A. W. Dow (8) stated that "If two pavement mixtures, alike in every way as to composition, voids, etc., are tested for stability, the one containing mineral aggregate with the highest adsorptive value will show the highest stability." In 1929 Prevost Hubbard (17) stated: "Indications point to the fact that whether or not adsorption is directly responsible, those sands with high adsorption values possess more pronounced stabilizing characteristics than those with relatively low adsorption values, so that the two may go hand in hand."

Included among the filler materials which Nicholson lists as having greater affinity for water than for asphalt are: Impure silica, gypsum, impure limestone and common clay. Among those with greater affinity for asphalt than water are pure limestone dust and hydrated lime.

Present indications are that both calcium chloride and common salt are retained longer in road mixtures containing limestone or slag. This suggests that as in the case of bituminous binders the lime materials have greater attraction for the chemical admixtures than the silica soils.

There is evidence that the fillers having the greatest attraction for the stabilizing admixtures tend to provide the entire mineral mixture with properties producing a stronger bond with the binder. In this respect fillers may perform an electrochemical as well as a mechanical function.

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[3] The above discussion concerns sodium- and calcium-ionized clays, found in nature or produced in the laboratory. How far it applies to chemically treated and thoroughly compacted road soil mixtures is not known. The ionized clays can come into existence only when water has completely leached out and replaced the chemical salts with which the clays may have been treated. Under no conditions then, are the properties of the sodium and calcium clays representative of the properties of the same clays which contain the calcium or sodium salts.

[4] See Stabilizing Sand and Gravel Surfaces, a paper presented before the Kansas Highway Conference, Manhattan, Kans., Feb. 5, 1934.

As early as 1910, Prevost Hubbard (*16*) described the effect of rock powders used to increase the bond in stone mixtures. Quotations from his book, Dust Preventives and Road Binders on this subject are as follows:

In another paper by Cushman on The Effect of Water on Rock Powders, the following conclusions are reached: (*a*) "When water comes in contact with most rock powders, immediate reactions take place, which are to a certain extent analogous to those which take place with cement and powdered glass." (*b*) "The microscope reveals an accumulation of amorphous material of a gummy appearance largely associated with the surfaces of the crystalline particles as the action of water proceeds." (*c*) "The effect of wet grinding is to increase the binding power or the cementing value of rock powders, and there are indications that the addition of small amounts of suitable electrolytes" (soluble inorganic salts, acids, and bases) "to the water will still further increase the action."

The last fact has a decided bearing upon the effect of blending different road-stones, one of which through being partially soluble is capable of reacting upon the other to produce binding films. It has been noticed in cases in which macadam roads were being constructed of hard material, such as granite or diabase, which are difficult to bond under the roller, that the surface quickly compacted and gave satisfactory results when treated with a top dressing of limestone screenings. This observation led Cushman and Hubbard to determine the cementing value of mixtures of these rocks with limestone as compared with the cementing values of the individual rocks. The results of a number of tests are given below and show conclusively that the addition of limestone to a feldspathic rock increases the binding power.

RESULTS OF TESTS OF THE CEMENTING VALUE OF GRANITE MIXED WITH LIMESTONE

Granite, serial no.	Limestone, serial no.	Cementing value		
		Granite	Limestone	Mixture
1431	1391	3	27	110
1432	1342	9	22	56
1435	1335	7	26	38
1435	1423	7	26	53
1574	1411	6	20	82

As the binding power of rock dusts is due to the decomposition or hydrolysis brought about by the action of water, it would follow that if this binding power can be increased by the addition of limestone it is caused by further decomposition of the material, brought about by the interaction of calcium hydroxide ($Ca(OH)_2$), resulting from the hydrolysis of the limestone particles. This is demonstrated by the following results obtained by determining the cementing value of a number of granites when treated with a small quantity of limewater, or calcium hydroxide solution.

RESULTS OF TESTS OF THE CEMENTING VALUE OF GRANITE MIXED WITH LIMEWATER

Serial no.	Cementing value		Serial no.	Cementing value	
	Alone	With limewater		Alone	With limewater
810	12	21	1276	11	31
811	6	16	1329	10	44
817	11	21	1398	6	18
893	12	16	1431	3	19
1008	35	45	1432	9	12
1192	14	27	1435	7	15
1275	16	39	1574	6	11

These results show in every case a considerable increase in the cementing value of granites so treated and would indicate that the addition of a small amount of lime might greatly improve the binding value of certain roadstones. Of course the addition of a sufficient quantity of lime would produce a mortar in which the bond due to the crystallization of calcium carbonate will cover up any actual increase in the cementing value of the

stone treated. This effect will also be produced to some extent when even a small quantity of lime is employed, but results given by Lord, who applied the principles developed by Cushman for rock powders, show that when a sample of chert and one of clinker were so treated the increase in cementing value was greatly in excess of that produced by treating a chemically inert slag in a similar manner. These results are given below and indicate that the increase in cementing value is due to the formation of a hydrated silicate of lime.

Material	Mineral composition	Cementing value				
		Alone	With 1 percent CaO	With 4 percent CaO	With 8 percent CaO	With 13 percent CaO
Slag	Olivene and gehlenite	8	15	33	52	95
Chert	Amorphous quartz	6	9	22	106	2,000+
Clinker	Acid silicate	4	24	60		1,400

PLASTICITY TESTS IMPORTANT IN SELECTING BINDERS

Instead of the chemical tests, the liquid limit and the plastic limit tests performed on the fraction of soil passing the no. 40 sieve are used to determine the relative capillary and cohesive properties of soils to be used as binders.

The liquid limit (*LL*) is defined as that moisture content, expressed as a percentage of the weight of the oven-dried soil, at which 10 light shocks will just cause the soil to begin to flow.

The plastic limit is defined as the lowest moisture content, expressed as a percentage of the weight of the oven-dried soil, at which the soil can be rolled into threads one-eighth inch in diameter without the threads crumbling.

The numerical difference between the liquid and the plastic limits is defined as the plasticity index (*PI*).

High liquid limits may be caused by capillary moisture, cohesive films, or a combination of both. Cohesionless mica flakes, spongy diatomaceous earth, and colloidal clay could all have a liquid limit, say, of 200. When such is the case the liquid limit of various mixtures of these materials would also be 200. Thus colloidal clay could be added to cohesionless diatoms in increasing amounts so that every degree of cohesion would be represented within the limits of the two materials without change in the liquid limits.

This is not true for the plastic limits. In cohesionless materials there is no plastic limit, which means, at least theoretically, that the plastic limit is equal to the liquid limit.

If the colloidal clay is added to the diatoms in increasing amounts, the plastic limits of the mixtures will decrease until the minimum of possibly 35 is reached, the plastic limit of the pure colloidal clay. Thus for equal liquid limits, the lower the plastic limit the greater is the indication of the presence of cohesive films and of plastic clays which furnish cohesion.

How the percentage of soil binder together with the accompanying capillarity required to produce a desired plasticity can be determined by means of data furnished by the plasticity tests has been suggested previously in PUBLIC ROADS (*12*). The amount of inert material required to reduce excessively high plasticity can also be determined from similar data.

Generally plasticity indexes of about 3 or less indicate sufficient binder cohesion for soil road surfaces to be constructed on locations subject to unusually wet conditions; indexes of 4 to about 8 for conditions of average moisture; and indexes of 9 to 15 inclusive only

for the drier or the arid conditions. Plasticity indexes exceeding 15 indicate soils not suitable for soil road construction.

The presence of the undesirable micaceous substances and diatomaceous, peaty, or other organic substances is indicated by liquid limits greater than those indicated by the expression $LL = 1.6\ PI + 14$.

The more the liquid limits exceed such values, the more unsatisfactory the soil binder is apt to be because of detrimental sponginess and capillarity. Elimination of such properties in detrimental amount from the final road mixture may be accomplished by keeping the liquid limits below 35.

For base courses the material passing the no. 40 sieve should have a plasticity index of not more than 6 and a liquid limit of not more than 25. The plasticity index and the liquid limit should be determined from tests conducted in accordance with standard A. A. S. H. O. and A. S. T. M. procedures.

EFFECT OF DELIQUESCENT CHEMICALS AND SOLUBLE BINDERS DESCRIBED

Granular material and binder are affected differently by traffic. The vehicle wheels will sink into roads of either pure dry sand or soft sticky clay. However, granular particles have a tendency to compact, whereas clays never lose the tendency to displace under traffic and form ruts. When a small amount of clay is mixed with granular material, the effect of the vehicle wheels is to force the sand grains closer together. Because of this, topsoil, gravel, and similar roads can, under proper conditions of maintenance, be developed into the densest of surfaces by traffic action alone, provided the surfaces are kept slightly moist. When such surfaces are dry, the binder powders under traffic and not only forms dust but also permits raveling of the surface, which leads to surface roughness and eventually to complete disintegration.

If, however, such surfaces can be maintained in a damp or slightly moist state, the binder will prevent the separation of the granular particles and the shocks and blows produced by vehicle wheels then become effective in wedging the granular fragments into close association. Thus the coarser stone, the sand, and the binder are compacted into hard road surfaces. Binder clay present in amount only slightly in excess of that required to coat the sand grains is gradually forced to the surface of the roads as the granular fragments consolidate, especially during wet weather, and is gradually carried off in the form of dust or worked to the sides of the road by traffic. In this way the gradings required for high stability may be automatically attained.

The importance of maintaining the proper amount of moisture in the surface cannot be overstressed. Absence of moisture from soil road surfaces causes dust and raveling. Too much moisture causes rutting. The drier the road surfaces become between rains the wetter they become when it does rain. This is because extreme dryness causes small cracks to form in the clay binder through which rain water may enter and soften the interior of the road surface. Fissures do not form in damp surfaces of properly graded roads. Consequently water is shed from them without injurious effect.

It is the function of the deliquescent chemicals to assist in maintaining moisture in the surface. Calcium chloride is sometimes used for this purpose. Magnesium chloride might also be of benefit. Under certain conditions of humidity and temperature such materials have the property of absorbing moisture from the air and slowing up the rate at which soils lose moisture between rains. Under certain other conditions they have the property of releasing their chemically combined moisture to the surrounding soil.

Sodium chloride functions mainly to retain the moisture already present in the soil and as a soluble binder that acts as a cement because of an interlacing of salt crystals formed in dry weather.

As the partially dried road continues to lose water, the solution of sodium chloride in the surface becomes concentrated to the saturation point and fine crystals are deposited, forming a cohesive sealcoat of salt and fine aggregate that appreciably retards further evaporation. Additional strength and stability are obtained through the crystallization of sodium chloride within the pores of the compacted mass as evaporation slowly proceeds. This filling of the voids minimizes the shrinkage which commonly accompanies loss of moisture, and thus reduces the tendency for shrinkage cracks to form. The importance of diminution of shrinkage in this way will be realized when it is considered that any shrinkage of the clay binder causes it either to crack or pull away from the coarse aggregates and thus allow the latter to become dislodged under traffic.

Treatment with either calcium chloride or sodium chloride (common salt) effects a decrease in the volume change and an increase in the density and stability of graded road mixtures; the calcium chloride does this through electrolytic and deliquescent properties, and the sodium chloride through electrolytic and crystalline properties. Generally, the surfaces treated with sodium chloride are harder, with a dryer appearance and slightly more dust, than the surfaces treated with calcium chloride.

Because solutions of calcium chloride and sodium chloride have lower vapor pressures than does water, the evaporation of moisture from soil mixtures wetted with these salt solutions is definitely slower than from similar mixtures moistened with water. These salts in a stabilized road mixture therefore tend to conserve its moisture.

The value of this ability to conserve moisture is most apparent during compaction of the stabilized mat in which the salt has been incorporated. The plasticity of the clay component is maintained over a longer time, thus prolonging the period during which compaction is taking place and permitting compression of the aggregate into a denser mass, with thinner and consequently stronger and more lasting binding films than would otherwise be obtained.

Roads treated with calcium chloride or sodium chloride may become coated with a thin layer of mud during wet weather. However it is believed that much of this is the result of an excess of soil binder or the use of a binder having too much plasticity. Use of these chemicals will not prevent loss of stability caused by faulty proportioning of soil materials in the mix. Proper grading of soil materials is an essential requirement in the stabilization procedures involving the use of either calcium chloride or sodium chloride. However, studies of the performance of more than 150 miles of salt-treated roads and approximately 2,000 miles of calcium-chloride treated roads indicate that, when used with properly designed soil mixtures, these chemicals have an important place in the highway field.

In the construction of soil base courses for either bituminous surface treatments or higher type wearing
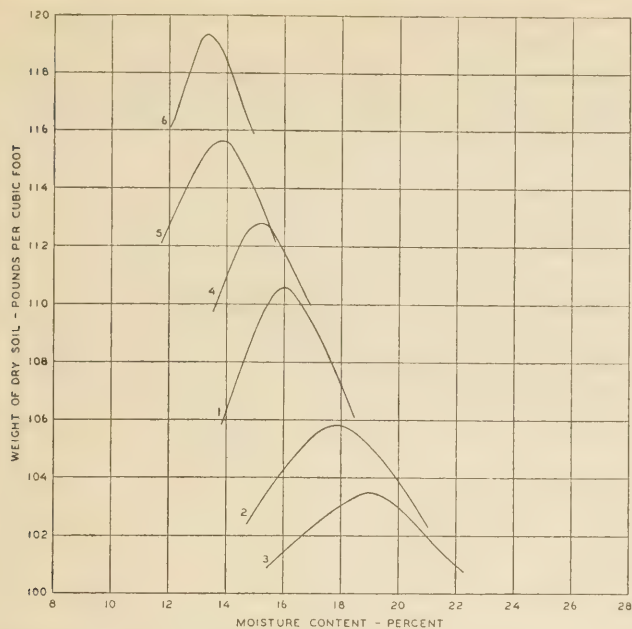
FIGURE 15.—EFFECT OF ELECTROLYTES AND FILLERS UPON THE DENSITY OF COMPACTED SOILS.

FIGURE 16.—EFFECT OF ELECTROLYTES UPON THE DENSITY OF COMPACTED SOILS.

TABLE 6.—*Effect of various admixtures on the optimum moisture contents and dry weights of various soils*

Soil admixture		Arlington		Iredell		Manor	
Kind	Amount	Optimum moisture content	Dry weight at optimum moisture content	Optimum moisture content	Dry weight at optimum moisture content	Optimum moisture content	Dry weight at optimum moisture content
	Pct.	*Pct.*	*Lb. per cu. ft.*	*Pct.*	*Lb. per cu. ft.*	*Pct.*	*Lb. per cu. ft.*
None		16. 1	110. 6	24. 6	100. 6	16. 3	108. 6
NaCl solution	5	13. 8	115. 8	18. 4	109. 6	14. 5	112. 4
CaCl₂ solution	5	14. 0	115. 4	20. 8	107. 5	15. 2	112. 2
Sodium hyposulphite	5	13. 3	119. 4	20. 9	106. 8	16. 5	110. 1
Hydrated lime	5	18. 0	105. 8	24. 3	98. 2	18. 2	104. 6
Soda ash	5	14. 9	114. 9	21. 7	104. 9	16. 6	112. 2
Sodium silicate	5	15. 3	100. 0	25. 7	94. 9	19. 0	102. 1
Ground slag	5	15. 0	112. 8	21. 8	105. 4	17. 5	106. 8
Ground limestone	5	16. 8	110. 0	18. 9	103. 3	16. 8	107. 2
Ferric chloride	5	14. 5	115. 5	22. 8	102. 9	17. 5	109. 0
Raylig [1]	5	11. 9	114. 1	23. 0	98. 5	13. 8	109. 0
Tannic acid	2	15. 4	110. 3	24. 1	97. 7	16. 5	106. 0
Cement	5	15. 2	112. 4	22. 4	101. 0	17. 1	103. 2
Bituminous material [2]	5	14. 0	109. 0	20. 8	98. 2	16. 5	103. 0

[1] Waste sulphite liquor.
[2] Applied in an emulsion.

courses the use of chemicals may be of especial benefit. Soil mixtures for bases should have lower clay content than that required in stable surface courses. Compaction of such bases by traffic prior to the application of the surfacing is desirable. Only by the use of water-retentive chemicals can base mixtures lean in binder be kept from dusting and raveling excessively under traffic.

The effect of salt solutions as well as other materials on the density of compacted soils is illustrated in figure 15.

Curve 1, figure 15, shows the dry-weight, moisture-content relation for the Arlington soil with no admixture. Curve 2 shows the relation for the Arlington soil containing an admixture of 5 percent by weight of hydrated lime. Curve 3 shows the relation for the soil with an admixture of 2 percent by weight of sodium silicate. Curves 2 and 3 are both below and slightly to the right of curve 1. The dry-weight, moisture-content relations for the Arlington soil with admixtures of 5 percent by weight of ground slag, curve 4, 5 percent sodium chloride, curve 5, and 5 percent sodium hyposulphite, curve 6, are shown in figure 15 by curves above and to the left of curve 1. For curves 2 and 3 the optimum moisture contents are greater and the densities less than for curve 1; the opposite is true for curves 4, 5, and 6.

Table 6 summarizes the results of a series of tests made to determine the effect of various electrolytes and other admixtures upon the compacted densities of the three soils. Figure 16 shows the effect of the quantity of sodium chloride admixture upon the compacted densities of the Arlington soil.

INSOLUBLE ADHESIVES RENDER SOIL RESISTANT TO CAPILLARY MOISTURE

Portland cement and bituminous materials are the admixtures that have been experimented with and used most up to this time. Other admixtures that might prove satisfactory are dual treatments with sodium silicate and calcium chloride to produce insoluble calcium silicate, also dual treatment with ferric chloride and ammonia to produce the highly adhesive ferric hydroxide.

In stabilization with insoluble adhesives, the fact that the films of adhesives might be thicker than those of moisture or solutions of electrolytes, at the same degree of soil compaction, has no significance with respect to the relative stability of the soil with the different films. The use of insoluble adhesives is not expected or intended to render the soil sufficiently hard or tough to resist the abrasive action of traffic, but simply to render the soil resistant to water from capillarity and thus to retain the same bearing strength that the soil has when in a dry, compacted condition.

In 1925 Goldbeck (*11*) reported the results of laboratory experiments which showed that additions of 5 percent of hydrated lime and portland cement have the effect of decreasing the volumetric change caused by variations in moisture content and likewise of increasing the bearing value of plastic soils that contain up to their limit of capillary moisture. The results of these tests are shown in figure 17.

Additional evidence that cohesive binders in soils are likely to prevent both their expansion and disintegration caused by water absorption resulted from tests that have been reported (*13*). Figure 18 shows six soil cakes representing soil existing at different depths in a subgrade located at Arlington, Va. The subgrade was treated with water-gas tar in 1923. These cakes were compressed in a semidry state, dried to constant weight, and immersed in water for 2 weeks in 1929. The two cakes shown on the left contained

NO. 1 SOIL D 1:20 PORTLAND CEMENT
NO. 2 SOIL D 1:20 HIGH CALCIUM LIME
NO. 3 SOIL D 1:20 HIGH MAGNESIUM LIME
NO. 4 SOIL D

EFFECT OF ADMIXTURES ON
THE VOLUMETRIC CHANGE

EFFECT OF ADMIXTURES
ON THE BEARING VALUE
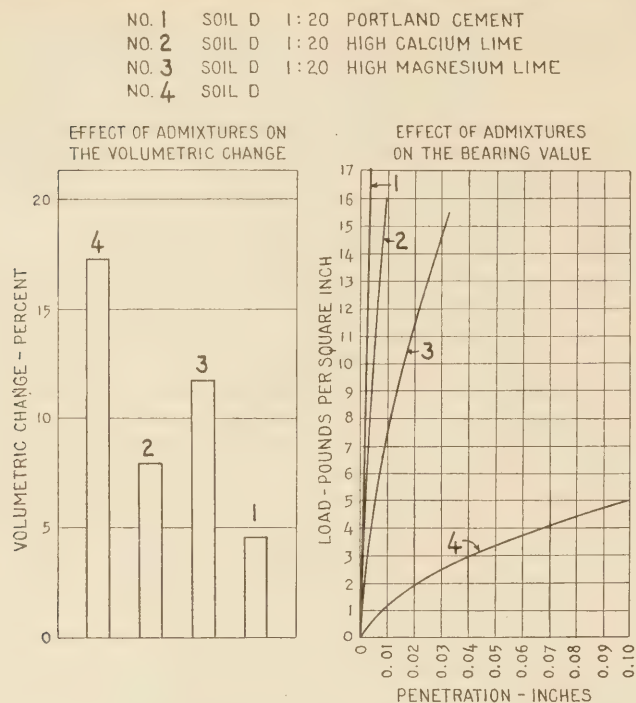
FIGURE 17.—EFFECT OF LIME AND CEMENT ON SHRINKAGE
AND BEARING VALUE OF A SOIL.

FIGURE 18.—UPPER; SOIL SAMPLES CONTAINING WATER-GAS
TAR IN VARIOUS AMOUNTS, PHOTOGRAPHED AFTER IMMER-
SION IN WATER FOR A PERIOD OF TWO WEEKS. LOWER;
THE EFFECT OF PORTLAND CEMENT AND BITUMINOUS MATE-
RIAL ON THE SLAKING PROPERTIES OF A SILT SOIL.

tar in appreciable amount and exhibited no signs of disintegration. The third cake from the left contained but a small amount of tar and crumbled to a slight degree along the top edges. The fourth cake from the left contained but a slight trace of tar and crumbled in appreciable amount near the top. The two cakes on the right contained no visible trace of tar and disintegrated to a marked extent.

Figure 18 also shows the effect of portland cement and bituminous material on a silt soil (14). Sample 1 was untreated and slaked completely when immersed in water for a few minutes. Sample 2 was treated with portland cement, and sample 3 with bituminous material. Both samples 2 and 3 showed no evidence of slaking during periods of immersion lasting several months.

Efforts to stabilize fine-grained soils by admixtures of lime and cement materials were made in Iowa and South Dakota as early as 1924 and in Ohio several years later. The results of early work were not particularly promising but they should not be considered as indicating the possibilities of such treatments, because the requirements of thorough distribution of admixture, high degree of compaction, and protective surface treatment now deemed necessary were not recognized in the earlier work.

More recent research on the use of portland cement for stabilizing soil bases was performed in South Carolina by the State highway department. The purpose of this work has been to develop a base material that could be constructed at less cost than that required to provide one of properly graded sand-clay or top soil.

Experimental work in the treatment of soils with bituminous materials has recently been conducted in various parts of the country. Sections of highway have been constructed using different grades of tars, road oils, and bituminous emulsions. Airplane landing fields have also been stabilized with bituminous materials.
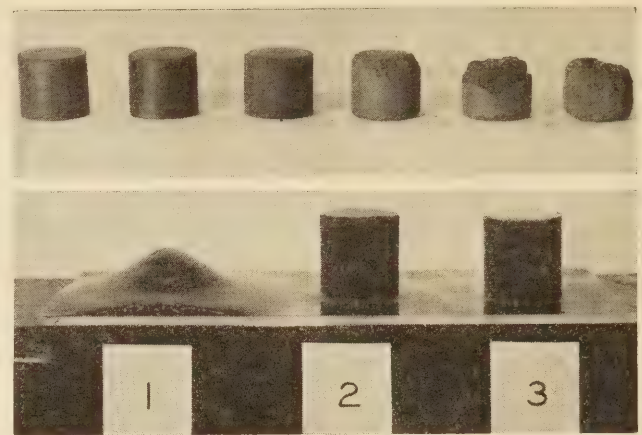
The use of the combined sodium-silicate and calcium-chloride treatment has been confined largely to the stabilization of coarse-grained soils supporting buildings and other structures.

VARIOUS METHODS USED IN SOIL ROAD CONSTRUCTION

The following is a general description of the best practice that has been developed to date in the construction of stabilized road surfaces. It should be used only as a general guide and it may be expected that better methods will be developed.

When a highway is built on a new location, a sufficiently wide roadbed or subgrade is first constructed, using available materials. Loose, sandy subgrades should be improved by the addition of soil binder; soft, unstable subgrades should be improved by the addition of granular material. The added material should be thoroughly mixed into the subgrade by harrowing or blading, after which the subgrade is brought to true alinement and grade by blading and rolling. Excess subgrade material that is suitable for use as binder for the wearing course can be bladed to the shoulders of the road and left in windrows during the preparation of the subgrade.

When an existing highway is improved, material is added or taken away to obtain the desired width, grade, and alinement. Soil binder or granular material is added in sufficient amount to obtain a stable mixture, and is thoroughly mixed into the subgrade by harrowing or blading.

There are three methods for obtaining the desired mixture—plant mixing and road mixing, and by using the "cut and try" method.

Plant mixing.—The essential requirements of a plant-mix job are a source of satisfactory binder in close proximity to the supply of coarse aggregate to be used; means for drying and pulverizing the binder; apparatus for measuring the quantities of binder and aggregate to obtain the proper proportions; and equipment for thorough mixing of the combined materials.

An ideal location for a mixing plant such as that shown in the lower picture in figure 19 is near a place

where the overburden consists of a clay soil having satisfactory binder properties. This overburden may be stripped and stockpiled in windrows so that it will dry sufficiently to be pulverized under a roller. The clay should then be combined with an aggregate of proper grading in such proportions that the resulting mixture will conform to the specifications. Thorough mixing should be provided by means of a pug mill or rotary-type mixer.

In some plant mixes, bank-run gravel and the existing overburden have been used and the drying and pulverizing steps have been eliminated by passing the combined materials through a rotary screen or over a grill to remove oversize material.

The mixture is hauled to the road, spread, sprinkled, shaped, and rolled. The principal advantage of the plant-mix method is that a more thorough mixing of the binder and aggregate is obtained.

Road mixing.—The necessary equipment for mixing the materials on the road includes tractor-drawn or self-propelled blade graders, scarifiers, harrows, and other apparatus for mixing, moistening, spreading, and compacting the base- and wearing-course materials. Scarifiers may be either of the four-wheel type or of the type attached to the roller. (See fig. 20A.)

Disk harrows should be such that unintended cutting into the subgrade can be avoided. Either the spring or spike-tooth harrows that assure positive control of the depth to which the teeth will penetrate are satisfactory. For mixing and shaping, power-drawn blade graders with a wheel base of not less than 16 feet are satisfactory. (See fig. 20B.) Multiple-blade maintainers may be of the truck-suspended or drawn type.

The surfaces of existing roads should be scarified deep enough to eliminate all irregularities of the surface and to permit reshaping to grade. After the loosened material is shaped to grade, the surface should be scarified to a uniform depth. New material, if required, should be spread on the loosened surface in amount sufficient to furnish a compacted layer of approximately 3 inches. If greater surface thickness is desired, additional layers should be constructed.

The material is mixed until it is uniform throughout by means of harrowing and turning with blade graders. The water required to obtain the proper moisture content in the wearing course is supplied in the following manner. After the mixture of binder and gravel is bladed onto the shoulders of the road, the base is moistened uniformly using a suitable sprinkler, and approximately one-fourth of the material from the windrows is bladed immediately onto the moistened base. The newly distributed road material is then similarly moistened and covered as before with one-fourth of the original windrowed mixture. These operations are repeated until the last layer of dry mixture has been placed.

Before moistening this top surface material, the road is shaped and compacted. Because properly graded mixtures contain enough granular material to provide for mechanical interlocking, a load applied at the top of an unconsolidated or partially consolidated layer is readily transmitted vertically and causes consolidation throughout the thickness of the layer. Consequently any means of applying adequate load whether it be a flat-wheeled roller, a crawler-type tractor, truck graders, other trucks, or vehicular traffic, will assist in the compaction of graded mixtures.
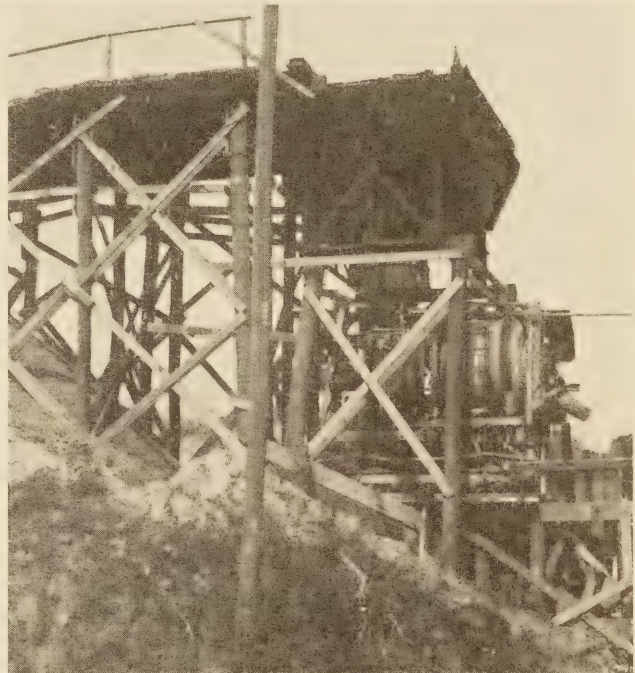
FIGURE 19.—MIXING EQUIPMENT USED IN STABILIZED SOIL ROAD CONSTRUCTION. UPPER; THE CLAY OVERBURDEN AND GRAVEL ARE MIXED IN PROPER PROPORTIONS AND LOADED DIRECTLY INTO TRUCKS. LOWER; THIS PLANT WAS USED TO MIX CLAY OVERBURDEN AND GRADED CRUSHED STONE FROM AN ADJACENT QUARRY.

After shaping and initial compacting are completed the surface is thoroughly dampened and again compacted.

During the period of final compaction the loose material should be kept distributed over the road surface by means of a road drag or blade grader. The amount of crown maintained by blading operations should be sufficient to provide for the rapid run-off of storm water in order to prevent the formation of pools of water on the road surface. Pitting of the surface is an indication that the crown is too slight.

"CUT AND TRY" METHOD USEFUL UNDER CERTAIN CONDITIONS

In the construction of roads on farms, and from farms to adjoining local roads, or under similar con-

FIGURE 20.—STEPS IN THE CONSTRUCTION OF STABILIZED SOIL ROADS. A, SCARIFYING A GRAVEL ROAD; THE LOOSENED AGGREGATE WILL BE USED IN THE STABILIZED MIXTURE. B, MIXING THE DRY MATERIALS WITH A BLADE GRADER. C, MIXING THE DRY MATERIALS FOR A CEMENT-TREATED ROAD WITH A DISK HARROW. D, COMPACTING THE WET MATERIALS ON A CEMENT-TREATED ROAD.

ditions where facilities for making precise determinations of grading of materials may not be available, the proper grading to furnish stability may be determined by "cut and try" methods.

The "cut and try" method has been used extensively in the construction of traffic-bound roads. Essentially, it consists of adding granular materials to surfaces that become excessively muddy during wet weather and adding clay soil to loose, sandy, and gravelly materials. The amount of either material added may vary considerably for different conditions and must be determined by trial. Usually, granular material is added in layers several inches thick. If, after this material is worked into the soil, a muddy condition persists in rainy weather, more granular material is added. If too much granular material is added the surface becomes loose and will not compact properly. Care should be taken to avoid adding an excess of clay to granular material, as when granular material is added to a clay surface the granular material may make up as much as 80 percent of the total surface course, but a very small amount of clay, possibly only 15 percent, will be required to stabilize loose sands and gravels. An effort should be made to powder the clay as finely as possible.

A sample of well-graded sand and binder soil may assist in the selection of soil mixtures that have the desired properties.

If a sample of well-graded material is wetted and squeezed in the hand, the following characteristics will be noted: (a) The soil is extremely gritty; (b) it can be formed into definite shapes that retain their forms even when dried; (c) if the clay alone adheres to the hands, it will only be enough to discolor them slightly; (d) if more than enough soil to discolor the hands adheres to them, it will consist of both sand and clay instead of clay alone; and (e) when the wetted sample is patted in the palm of the hand it will compact into a dense cake that cannot be penetrated readily with a blunt stick the size of a lead pencil. These characteristics indicate well-graded material. The grittiness of the sample indicates the presence of sufficient granular material. Development of some strength on drying indicates a sufficient amount of binder soil. Resistance to the penetration of the pencil or stick, even when the sample is thoroughly wetted, indicates a desirable interlocking of the grains and the presence of a sufficient amount of capillary force.

Too much sand would cause the sample to fall apart when dried. Too much clay would leave the hand muddy after the wet sample was squeezed and would cause the wet sample after being patted to offer little resistance to the penetration of the stick.

ADMIXTURES APPLIED BY SIMPLE METHODS

In plant mixing, calcium chloride is generally added to the mixture at the plant. In road mixing calcium chloride is applied in the following manner:

After the new and old soil materials have been spread over the prepared base in sufficient thickness, they

should be covered uniformly with flake calcium chloride in the amount of ½ pound per square yard per inch of thickness, with a maximum of 2 pounds per square yard. The spreaders should be capable of spreading the chemical uniformly and in the desired quantities. The calcium chloride is then thoroughly worked into the soil by harrowing and blading until the surfacing material is uniform throughout. Sprinkling and shaping into a finished surface is then accomplished in the same manner as in the case of the untreated roads already described.

In construction using the cut-and-try method, calcium chloride may be applied to the road surface after its condition indicates that a proper gradation of materials has been obtained. The chemical may be applied by mechanical spreaders as on road mix jobs or it can be conveniently spread by means of a hand shovel.

Calcium chloride should not be applied during periods of cold, wet weather. The most favorable time for a surface application of calcium chloride is during the drying period just following a rain, after the surface has been bladed to proper smoothness. The moisture in the road at that time hastens solution and penetration. In the absence of rain, application in the early hours of the day, when the air has high relative humidity, is very desirable. Calcium chloride applied just prior to a rain will probably be washed off the road and consequently afford little or no benefit. When blading of the calcium-chloride treated road is required, it should be done after rains or commenced near the end of a rain. At other times the surfaces may be too hard. For patching holes an admixture of 100 to 150 pounds of calcium chloride per cubic yard of graded soil is recommended.

Need for extensive patching during dry weather can be minimized or eliminated by periodic maintenance with light applications of calcium chloride during the season.

In the use of calcium chloride as a dust palliative, it has long been known that this material remained effective for much longer periods in gravel having a clay binder than in gravel having a sandy filler. It has also been apparent that the presence of loose gravel tended to shorten the useful life of a treatment. The intermittent movement of such loose gravel by traffic and maintenance operations exposes new surfaces to the air and promotes evaporation.

Sodium chloride may be added at the plant for a plant mix or to the mixture on the road for a road mix. Rock salt has been used most generally, but any commercial type of pure salt or salt brine is satisfactory. The coarser grades of rock salt are well adapted for stabilization, as they remain free-flowing and can be more uniformly spread than the finer gradations, which will absorb moisture and cake when stockpiled along the road. The salt should contain not less than 98 percent of pure sodium chloride.

When sodium chloride is applied in the form of brine any of the gradations of the salt may be used, since the condition of the salt before it is dissolved is unimportant. The stabilized mixture will remain plastic longer if all of the salt has been dissolved, thus permitting rolling and compacting to be continued over a long period of time with the possibility of attaining greater ultimate compaction. There should be enough water to moisten the soil somewhat above the plastic limit.

In Indiana it was found that from ¾ to 1¼ gallons of water per square yard per inch of thickness were needed to moisten the mixture satisfactorily. This was slightly more than 20 percent by weight of the soil fines. If there is overwetting of the surface mixture, there is danger of vehicles cutting through the surface course and mixing it into the subgrade.

Water is usually added by means of pressure distributors, sprinkler wagons, or gravity tank trucks. It is preferable to make several trips over the section under construction, sprinkling lightly on each trip. This gives the moisture a chance to penetrate sufficiently and does not result in a sloppy condition on the surface. The amount of salt used varies somewhat in the different States. The usual amount is about 2 pounds per square yard per 3-inch thickness of road constructed. Indiana requires ¾ pound per square yard per inch thickness, regardless of thickness of the road constructed.

During prolonged dry periods the fine aggregate may wear off of a sodium-chloride treated surface, leaving the larger aggregate particles protruding. This condition can be corrected by covering the surface to a depth of about ½ inch with properly proportioned soil mixtures containing about 100 pounds of sodium chloride per cubic yard. When damp the mixture makes a satisfactory bond with the worn surface without scarification.

If, during periods of rainfall, the top eighth or quarter of an inch of stabilized roads becomes plastic, crushed aggregate should be added to the surface in amounts of about 50 to 70 tons per mile. This aggregate should have a maximum size of about ½ inch and should be free from dust and sand. The material should be spread over the surface and kept uniformly distributed as long as the surface is wet. The thin surface layer of fines acts as a cementing agent for the coarse aggregate that has been added. This results in a satisfactory driving surface, adds some additional thickness to the road, fills up any depressions that may have developed, and reduces the tendency for pot holes to form.

STABILIZATION OF FINE-GRAINED AND POORLY GRADED SOILS REQUIRES SPECIAL CARE

Practice in the stabilization of fine-grained soils differs in several respects from the procedures used in the construction of roads with well-graded mixtures. Care must be taken to provide for the optimum moisture contents when only water or electrolytes are used as admixtures, because it is particularly important to obtain the maximum density.

Special means are needed to insure uniform distribution of all materials when cement and bituminous materials are used as binders and when crushed rock, slag, etc., are used as primers or neutralizers. This is because of the much greater surface area to be covered in the fine-grained materials. A cubic foot of sand composed of grains 1 millimeter in diameter has a total interstitial surface area of about 1,000 square feet; that of the same volume of silt composed of grains 0.02 millimeter in diameter is about 50,000 square feet, or more than 1 acre; and that of a cubic foot of material composed of grains only 0.001 millimeter in diameter is about 1,000,000 square feet, or about 23 acres. It has been estimated that a cubic foot of ordinary loam soil has a surface area of about 1 acre, and that of an equal amount of fine clay soils is about 4 acres.

Compacting equipment designed to produce a predetermined degree of densification during construction must be used, instead of depending upon traffic to produce the maximum density afterward, although traffic may cause a slight increase in density under certain conditions. When coarse particles are absent, or are present in such amounts that they are surrounded by the cohesive, fine-grained particles, the effect of a load applied to a layer of such material is to consolidate that portion immediately beneath the load without adequately compacting the particles in the lower part of the layer. Consequently, rolling fine-grained soils with a flat-wheel roller may produce undesirable stratification and insufficient consolidation. The prongs of a sheep's-foot or tamping-type roller, or equipment that produces similar effect, are required to penetrate the unconsolidated material and compact the layer from the bottom upward in order for the layer to be consolidated uniformly throughout its thickness without stratification.

When only water or electrolytes are used as admixtures, it is especially important that the soils should be compacted by means of a sheep's-foot roller, or apparatus giving similar effect, at optimum moisture content and to a density indicated by the Proctor tests. Construction with admixtures of portland cement and bituminous materials does not require such extreme care in order to obtain satisfactory results.

Bituminous surface treatments are required to provide fine-grained soil roads with the resistance to abrasion and softening under traffic furnished by the coarse aggregate in graded soil mixtures.

Stabilization with cement and bituminous materials.—The construction methods used on experimental work in South Carolina (*23*) were substantially as follows: The cement was spread on top of the pulverized soil at the rate of about one sack per linear foot of roadway 18 feet wide. The dry soil and cement were mixed with disk harrows supplemented by a disk plow or road machine (fig. 20c). Water was then added at the rate of about 8 gallons per linear foot and compaction was accomplished by means of loaded trucks with dual tires (fig. 20d). The surface was finished with a blade grader after compaction. A bituminous surface treatment was applied subsequently to provide against surface abrasion.

All of the experimental sections are reported to be in good condition at the present time and no disintegration has been observed.

Construction with bituminous emulsion is illustrated by a project in Solano County, Calif., described by C. L. McKesson (*21*). Laboratory studies indicated that the natural adobe clay soil could be stabilized to a depth of 3 inches with about 3 gallons of 55 percent emulsified asphalt. By adding 2 parts of quarry waste to 1 part of the clay, stabilization was accomplished with 1 gallon of emulsion per square yard, a saving after paying for the quarry waste of about 5 cents per square yard. The construction methods were as follows:

The quarry waste was uniformly spread on the clay subgrade to a loose depth of 1¼ inches and scarified into the natural clay. The loose mixture was 4½ inches thick. The clay and quarry waste were well mixed by harrowing.

The soil mixture was then dampened with about 2 gallons per square yard of water and the water was mixed in by harrowing.

The emulsified asphalt was then applied, after dilution with four parts of water (fig. 21).

The diluted emulsified asphalt was applied in six applications. After the first application of emulsion the mixture was harrowed and then the top inch of the mixture was bladed to the sides. This was repeated after the next two applications of emulsion. The soil mixture was then in two windrows on the sides, and was distributed back over the road in three spreads and dilute emulsion was applied to each.

To obtain thorough mixing, the soil-emulsion mixture was again bladed into windrows and then brought back in thin layers and finally shaped to the required cross section.

The tractor used to pull the mixing equipment had by this time fairly well compacted the road surface. The lower picture in figure 21 illustrates the compacting operation as performed on a similar job.

One gallon of emulsion and 6.2 gallons of water were used per square yard, including the water used in the preliminary dampening operation.

This completed the soil stabilization and there remained only the surface treating.

The surface was then given an application of approximately ¼ gallon per square yard of the emulsion, diluted with an equal part of water and immediately covered with 40 pounds per square yard of ½ to ¼ inch crushed stone.

The surface of the road was then rolled. The crushed stone was embedded in the stabilized soil mixture. A final application of 0.64 gallon per square yard of undiluted emulsified asphalt was then spread and immediately followed with 15 pounds per square yard of ¼ inch to no. 10 sieve crushed stone, followed by brooming and rolling.

The road was not closed to traffic at any time during the construction of this project. Upon completion the road resembled bituminous macadam in appearance. This road came through the rainy season in perfect condition although the subgrade was saturated and plastic.

STABILIZATION PROCEDURES NOT STANDARDIZED

It should be kept in mind that other procedures using portland cement and bituminous materials in soil stabilization are in a state of development and those just described are given as examples. Numerous experiments are being carried on, some involving use of the optimum moisture content as disclosed by the Proctor tests and compaction with sheep's-foot rollers, while in others traffic is largely depended upon for compaction.

An experimental stabilized road in Jackson County, Mo., (*10*), was compacted by traffic. Asphaltic materials used as stabilizers were introduced at desired depths below the surface of the loose road mix by means of a specially constructed "sub-oiler" illustrated in figure 22. It is essentially a tooth scarifier having an oil line attached to the back of each tooth and running nearly to its points.

The theory back of this procedure has been that as moisture evaporates from the overlying soil the moisture films will be replaced by liquid asphalt. The report states that roads consisting of heavy, sticky clay or gumbo types of soil are water resistant after treatment and unaffected by rains.

Another method for incorporating the asphalt into the soil was tried in Missouri during 1935 (*26*). The clay surface was scarified, and the loosened material
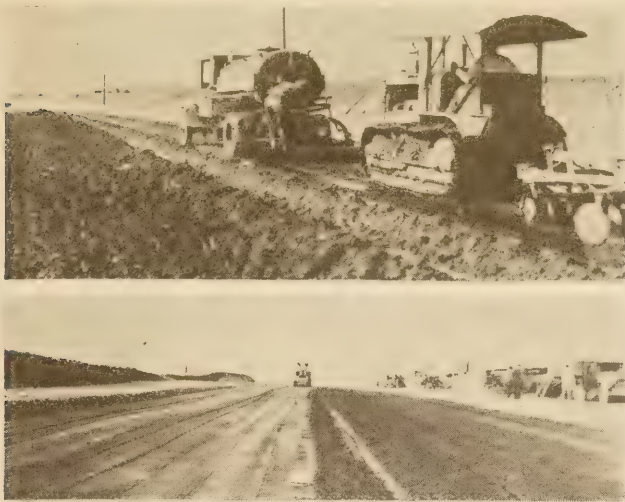
FIGURE 21.—UPPER; APPLYING BITUMINOUS EMULSION AND MIXING WITH A DISK HARROW. LOWER; ROLLING A BASE COURSE STABILIZED WITH BITUMINOUS EMULSION.

FIGURE 22.—SUB-OILER FOR APPLYING BITUMINOUS MATERIAL IN SOIL STABILIZATION.

windrowed and mixed with the desired percentage of bituminous material by means of a traveling mixing plant. Prior to scarifying, varying quantities of aggregate were added to test the efficiency of additional coarse material in case too great a degree of plasticity was induced, and also to check the relative efficiency from the viewpoint of economical construction.

About 35 gallons of water per cubic yard of mixed material were added to facilitate mixing in the pug mixer. The sections that had time to dry prior to freezing carried traffic with little or no signs of distress, although there was some evidence of a sponginess or rubbery action indicating that future additional consolidation would and should take place.

The use of tar in soil road stabilization has been described (*37*). The tar used consisted of two grades. Grade 1 tar had a specific viscosity of 4 to 8 (Engler) at 40° C., and grade 2 tar had a specific viscosity of 26 to 36 (Engler) at 50° C.

After the road was graded and shaped the soil was pulverized over a width of 22 feet. Grade 1 tar was added to the loosened soil, thoroughly mixed in, and the mixture windrowed. Grade 2 tar was added later and the mixture spread and compacted by traffic.

The moisture content of the soil varied from 2.9 percent to 7.5 percent at the time the tar was added. About 1.4 gallons of grade 1 tar per square yard and about 2 gallons of grade 2 tar per square yard were required.

A tack coat of about 0.26 gallon of grade 2 tar per square yard, covered with sand, was applied to the surface to prevent dusting under traffic. A bituminous wearing course was to be applied later.

Soon after this section of stabilized road was constructed, the following observations were noted.

1. A very light-viscosity tar mixed with soil results in a mixture that is very resistant to water.

2. Unless a tar mixture is covered by a seal coat very soon after it is mixed a portion of the tar will apparently disappear.

3. Small lumps of clay soil do not seem to cause any trouble if the lumps are surrounded by material impervious to water and protected from traffic.

Determination of the moisture content and degree of densification of the material being placed by means of the tests suggested by Proctor are important in many types of soil stabilization. The moisture contents are determined by packing the wet soil in the Proctor cylinder, weighing, measuring the resistance to penetration, and comparing these values with the laboratory curves for wet weight and resistance to penetration for the particular sample. Checks on these values may be made by oven-drying small samples to determine the moisture contents more accurately. If the soils are found to be below the optimum moisture content they are sprinkled with water, and if found to be above the optimum they are spread in thinner layers and allowed to dry either before rolling or during longer rolling periods.
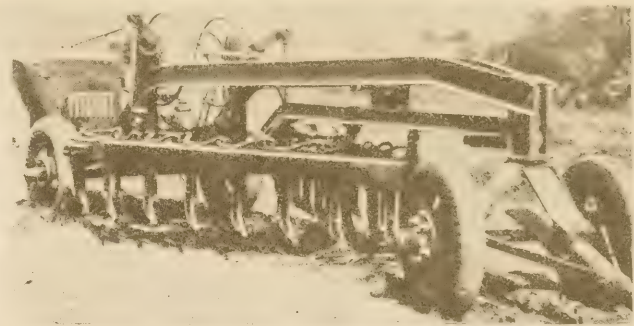
The extent of consolidation is determined by measuring the resistance to penetration of the soil layer in place, and comparing the values with the readings obtained when the same soil was compacted in the standard manner in the cylinder. If the plasticity needle readings for the soil layer are less than those for the soil in the cylinder, more rolling will be required. This test is not used as extensively as the dry weight test because the presence of gravel in the material interferes with the needle and gives distorted values.

Check tests on the degree of consolidation are made in the following manner. Approximately 15 pounds of the compacted soil are removed from the layer with a post-hole auger and weighed. The same soil is then packed in the Proctor cylinder, weighed, and the density and moisture content computed as in the regular tests. The hole from which the material has been taken is filled with sand of a known loose weight per cubic foot and the volume thus measured. The wet and dry densities of the compacted material are determined from the weight, moisture content, and volume. A comparison of the densities of the wet soil in place and the same soil compacted in the cylinder in the standard manner immediately indicates whether more rolling is required or whether less rolling will suffice.

SUMMARY

Substantial progress has been made in obtaining a better understanding of the basic theories of soil stabilization and the manner of applying them in the design and construction of stabilized roads.

Data on the effect of temperature, degree of compaction, and grading, and data on the use of admixtures of electrolytes, fillers, neutralizers, and insoluble binders indicate that:

1. The outcome may be unsatisfactory when clay soils are compacted to a given extent without regard to moisture content, or when compacted with a given moisture content without regard to the type or extent of compaction.

2. Soils compacted to maximum density at low temperatures may soften due solely to the water liberated from the adsorbed films by a rise in temperature.

3. For equal amounts of compacting, greater densities can be attained at high temperatures. To obtain the same densities more work of compaction will be required at low temperatures.

4. For equal work of compaction, well-graded mixtures become the densest.

5. Admixtures of granular aggregate may effect a three-fold change: (a) Improve the quality of the clay due to electrochemical phenomena, (b) reduce the surface area per unit volume, and (c) increase the internal friction of the mixture. The low silica types and the alkaline clays are likely to make the best binders. Other clays may be improved by admixtures of slag, crushed stone, and gravel.

6. In the construction of fine-grained base courses it is felt that the use of the insoluble binders such as portland cement and bituminous materials is likely to prove more satisfactory than attempts to stabilize with moisture films alone.

7. Mixtures of acidic and basic rocks show a higher cementing value than either alone. It seems possible by selecting and blending certain road stones or by treating the road with a suitable chemical salt or base to increase greatly the natural bond at the road surface.

8. It is especially essential that mixtures having the proper characteristics be used in the construction of base courses. They should be used also in surface courses, but trouble developing here due to the use of unbalanced combinations of materials may be corrected as a maintenance measure. A similar trouble in base courses cannot be so easily corrected and consequently may result in expensive failure of the entire road structure.

That mixtures with clay binders have served satisfactorily as road surfaces is no assurance that they will not fail completely under the almost continuous moist conditions produced when evaporation is stopped by coverings of impervious wearing courses. Without a thorough knowledge of the swelling properties of soil binders, the risk of failure that attends the practice of constructing impervious wearing-courses on soil-bound mixtures that have become highly stable under traffic cannot be overemphasized.

9. It seems feasible to use admixtures of electrolytes and fillers to obtain the desired densities when compacting the more porous soils, and to decrease the amount of compacting required to consolidate soils of the better grades. When in the semisolid state, soils require greater amounts of compacting than when in the plastic state. As a practical consideration, therefore, it seems desirable to consolidate fine-grained soils in the plastic state (where the films act as lubricants) but near enough to the plastic limit so that evaporation during compacting will be sufficient to leave the finally compacted soil in the semisolid state (where the films act as adhesives). Soils with optimum moisture contents slightly below the plastic limit and with initial moisture contents for mixing and compacting slightly above seem to provide a favorable balance between lubricating and adhesive properties.

10. The success of road construction in the low-cost field demands that special attention be directed toward simple operations and the use of local materials. Nevertheless, the importation of commercial aggregates and fines to improve the quality of soils of poorer grades may be advisable in the interests of ultimate economy of construction and maintenance and of type of service rendered.

More than 2 million miles of our rural roads are unimproved. Developments in the field of soil stabilization will make possible the improvement of greater mileages of these roads with the funds available.

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STATUS OF FEDERAL-AID HIGHWAY PROJECTS

1936 FUNDS

AS OF APRIL 30, 1936

STATE	APPORTIONMENT	COMPLETED			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR NEW PROJECTS
		Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$2,604,320	$493,754	$369,334	39.9	$1,480,629	$1,218,797	61.6	$62,666	$28,641		$2,604,320
Arizona	1,781,347										164,575
Arkansas	2,142,723										2,142,723
California	4,756,959	338,250	195,232	7.5	4,550,418	2,603,359	88.3	1,996,526	1,149,995	60.5	808,373
Colorado	2,288,811	399,025	222,933	21.6	2,076,115	1,227,676	72.5	907,493	422,404	10.2	838,202
Connecticut	791,253				364,334	176,660	4.8	185,689	92,844	4.1	192,189
Delaware	609,375				263,927	131,964	30.3	218,968	109,484	8.7	384,567
Florida	1,655,723	292,520	164,327	44.6	814,632	407,316	27.5	1,491,550	745,775	80.5	1,138,923
Georgia	3,168,221				979,489	459,220	74.6				1,963,226
Idaho	1,531,162	247,908	123,949	6.9	1,594,511	952,062	127.6	64,242	38,442	6.0	376,331
Illinois	5,160,696	224,362	105,460	57.5	5,690,571	2,842,931	92.1	2,762,116	1,344,057	38.8	973,708
Indiana	3,087,613				5,086,554	2,543,267	173.5	557,283	278,519	21.4	141,873
Iowa	3,231,718	162,776	81,388	145.1	4,879,949	2,299,215	215.2	1,588,532	743,973	130.6	83,070
Kansas	3,317,054	604,406	302,203	39.4	2,254,336	1,127,168	157.1	1,829,149	914,574	209.4	1,193,924
Kentucky	2,304,143				1,564,765	762,800	102.3	1,450,355	690,896	37.7	548,244
Louisiana	1,776,939	190,485	95,242	4.9	1,832,314	916,157	66.5	878,383	439,192	29.8	326,348
Maine	1,090,167	113,605	56,803	2.1	1,598,729	799,364	51.5	191,524	95,762	4.1	138,238
Maryland	1,025,870										1,025,870
Massachusetts	1,741,877	1,028,185	512,595	33.2	333,935	166,968	3.1	1,925,250	962,625	81.8	1,574,909
Michigan	3,837,292	350,412	145,842	12.2	4,213,918	2,104,234	152.0	2,792,640	1,384,680	191.7	257,838
Minnesota	3,423,306				3,505,244	1,524,512	253.5				368,272
Mississippi	2,196,524	1,126,860	562,809	221.1	3,160,360	1,580,179	126.4	1,494,627	747,314	62.0	2,196,524
Missouri	3,800,856	661,394	370,182	141.9	2,786,348	1,560,076	186.3	1,076,228	602,580	97.6	910,554
Montana	2,560,449										27,611
Nebraska	2,581,663	1,104,139	552,023	66.5	655,606	347,165	73.4	150,049	75,025	16.3	1,607,450
Nevada	1,595,501	232,553	200,035	74.0	905,998	784,321	93.0	171,338	148,328	28.3	462,817
New Hampshire	609,375				760,912	374,109	22.2	141,629	70,736	1.9	164,530
New Jersey	1,675,751	50,782	25,391		2,067,366	1,033,683	29.7	1,321,388	574,163	10.4	42,514
New Mexico	1,999,299	159,058	96,739	18.4	2,044,483	1,243,454	147.0	624,267	379,679	18.5	279,427
New York	6,150,106				9,226,855	4,559,450	165.6	2,021,775	1,011,862	30.8	578,794
North Carolina	2,938,657	87,050	43,525	15.2	1,310,435	652,752	212.4	1,790,335	876,800	187.6	1,265,580
North Dakota	1,960,162							187,005	101,941	.1	1,858,221
Ohio	4,565,435				2,785,282	1,392,342	40.3	3,206,410	1,448,115	38.0	1,754,978
Oklahoma	2,947,521	52,070	27,363	2.1	1,674,653	877,775	56.0	769,596	404,422	21.3	1,637,961
Oregon	2,044,653	191,986	116,264	4.1	2,672,073	1,628,599	91.3	457,854	266,128	14.0	33,642
Pennsylvania	5,348,062	60,985	30,492	1.6	5,229,340	2,614,670	77.2	2,412,428	1,205,369	34.1	1,497,531
Rhode Island	609,375				50,787	25,393	35.2	34,891	15,701	8.7	609,375
South Carolina	1,692,896				516,850	283,389	56.9	644,924	384,877	95.9	1,651,802
South Dakota	2,036,775										1,368,509
Tennessee	2,638,159	126,573	63,286	5.1	1,372,457	686,229	354.6	111,392	55,696	4.1	1,832,948
Texas	7,777,504	2,360,023	1,178,103	137.0	6,276,989	3,133,066	85.9	3,520,848	1,718,407	176.9	1,747,928
Utah	1,410,752	269,089	189,239	17.0	1,243,850	873,988	52.2	341,101	244,015	16.5	105,510
Vermont	609,375	22,052	10,786	2.9	1,136,311	568,156	69.8	39,201	19,600	4.2	10,833
Virginia	2,278,475				1,737,000	868,500	62.8	937,550	493,775	28.1	916,201
Washington	1,949,957	637,516	335,555	20.5	2,158,296	1,135,649	36.5	307,946	162,000	8.2	316,752
West Virginia	1,356,793	87,161	43,581	3.0	754,175	377,087	75.5	340,482	170,229	9.1	765,896
Wisconsin	3,045,557	511,344	255,672	18.9	1,692,693	843,754	185.7	1,235,120	667,560	43.7	1,278,571
Wyoming	1,553,444	627,026	385,138	88.9	1,855,155	1,127,460		46,782	23,391		22,855
District of Columbia	609,375				228,629	113,760	2.5	38,429	17,787	1.0	477,828
Hawaii											
TOTALS	**121,875,000**	**12,813,349**	**6,862,091**	**1,253.4**	**97,387,273**	**50,948,676**	**4,092.4**	**42,385,961**	**21,297,363**	**1,877.6**	**42,766,870**

CURRENT STATUS OF UNITED STATES WORKS PROGRAM HIGHWAY PROJECTS

(AS PROVIDED BY THE EMERGENCY RELIEF APPROPRIATION ACT OF 1935)

AS OF APRIL 30, 1936

STATE	APPORTIONMENT	COMPLETED			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR NEW PROJECTS
		Estimated Total Cost	Works Program Funds	Miles	Estimated Total Cost	Works Program Funds	Miles	Estimated Total Cost	Works Program Funds	Miles	
Alabama	4,151,115	427,711	424,474	34.7	3,073,743	3,073,743	97.5	560,971	560,971	13.3	516,401
Arizona	2,569,841	45,829	45,829	1.6	1,572,917	1,356,156	102.3	789,729	399,819	47.0	389,392
Arkansas	3,352,061				1,919,177	1,916,407	152.7	1,074,770	1,061,564	154.6	328,262
California	7,747,928	83,325	79,100	16.2	5,580,393	5,385,993	200.7	129,479	123,037	1.2	2,159,798
Colorado	3,395,363	315,119	315,119	23.6	1,371,127	1,370,736	60.5	146,039	146,039	3.3	1,563,369
Connecticut	1,418,709				220,811	202,552		119,852	115,783	.2	1,100,374
Delaware	900,310				412,363	412,362	34.6	124,520	124,520	24.2	363,428
Florida	2,597,144				1,556,380	1,538,508	60.3	636,930	636,930	16.3	421,706
Georgia	4,988,967				433,342	433,342	29.0	303,348	303,348	19.3	4,252,276
Idaho	2,222,747	9,995	9,995	.2	1,356,932	1,347,258	106.2	265,159	246,255	24.4	629,233
Illinois	8,694,009				5,599,205	5,599,205	274.1	1,965,613	1,965,613	170.3	1,119,196
Indiana	4,941,255				3,354,345	3,354,345	173.7	1,416,736	1,416,736	58.8	170,174
Iowa	4,991,664	15,034	14,100	6.6	1,940,712	1,846,115	141.9	1,178,529	1,120,180	186.8	2,011,269
Kansas	4,994,975	34,551	34,551	20.4	2,541,804	2,541,804	228.0	1,896,266	1,896,266	123.3	522,354
Kentucky	3,726,271	9,896	9,896	1.7	1,492,649	1,492,649	214.9	1,318,688	1,312,221	108.8	911,505
Louisiana	2,890,429				594,067	472,801	28.6	1,172,919	1,137,215	124.9	1,280,413
Maine	1,676,799				778,761	778,497	35.9	806,057	805,774	33.4	92,528
Maryland	1,750,738				38,893	38,893	1.9	481,161	440,549	23.5	1,271,296
Massachusetts	3,262,885	449,100	449,100	25.4	117,754	117,754	1.1	412,000	412,000	17.7	3,145,131
Michigan	6,301,414	175,517	175,517	46.6	5,273,771	5,213,741	237.0	2,678,542	2,331,496	585.1	226,573
Minnesota	5,277,145				1,849,853	1,734,039	159.2	1,110,092	1,110,092	94.6	1,136,094
Mississippi	3,467,552	206,655	206,655	110.8	2,034,717	2,031,623	113.3	1,941,992	1,939,891	192.0	315,837
Missouri	6,012,652	42,612	42,612	2.3	2,830,893	2,830,657	466.9	688,872	688,872	19.8	1,035,448
Montana	3,676,416				2,888,821	2,888,821	163.5	1,056,774	1,056,774	117.6	56,112
Nebraska	3,870,739				1,878,727	1,837,755	192.9	190,605	182,292	15.0	976,210
Nevada	2,243,074	133,492	133,492	5.1	1,522,471	1,482,902	59.9	124,244	124,244	1.2	626,680
New Hampshire	945,225				335,780	322,876	9.9	469,299	469,299	39.4	440,057
New Jersey	3,129,805				2,014,617	2,014,617	12.9				990,944
New Mexico	2,871,397	242,997	242,997	29.6	1,588,069	1,588,069	101.9				571,031
New York	11,046,377				6,951,408	6,533,608	66.3	3,325,630	3,325,630	34.9	1,187,139
North Carolina	4,720,173	156,966	156,966	21.4	2,125,251	2,092,662	161.7	1,140,418	974,149	48.8	1,496,396
North Dakota	2,867,245	156,290	156,290	20.9	319,019	319,019	49.0	1,064,333	1,064,333	126.2	1,327,603
Ohio	7,670,815	15,590	15,590	.3	3,156,689	3,094,689	34.0	1,361,000	1,291,025	53.1	3,269,511
Oklahoma	4,580,670				1,204,024	1,203,923	94.5	2,028,438	2,028,351	229.4	1,348,396
Oregon	3,038,642				1,900,556	1,890,556	79.6	905,181	819,864	82.1	328,223
Pennsylvania	9,347,797				420,145	420,145	12.1	1,959,167	1,893,471	84.8	7,034,182
Rhode Island	989,208	7,184	7,184	2.4	633,415	633,415	13.8	346,746	346,746	5.3	1,863
South Carolina	2,702,012	47,193	47,193	30.1	647,925	625,771	62.6	1,341,523	1,336,623	125.2	692,424
South Dakota	2,976,454	79,686	79,686		1,021,925	1,021,925	233.5	602,105	602,105	87.9	1,272,737
Tennessee	4,192,460				1,290,520	1,290,520	52.5	1,018,647	1,018,647	41.8	1,883,294
Texas	11,389,350	366,574	325,521	43.8	8,124,894	7,386,753	694.3	3,294,536	3,243,936	329.0	1,033,140
Utah	2,067,154	83,950	83,784	2.7	893,467	867,438	81.0	488,354	444,004	35.7	671,929
Vermont	924,306				479,971	447,661	11.0	460,514	410,386	10.3	66,259
Virginia	3,652,667	78,821	78,820	71.5	1,656,703	1,654,966	673.2	1,077,373	1,059,510	29.9	859,370
Washington	3,026,161	45,612	44,615	8.3	2,450,438	2,226,431	120.7	428,829	385,003	17.5	370,112
West Virginia	2,231,412				1,098,894	1,098,894	44.5	482,332	482,332	21.1	650,186
Wisconsin	4,823,884	60,230	50,000	1.3	3,016,692	2,663,756	152.4	1,842,522	1,817,805	161.2	292,323
Wyoming	2,219,155				1,654,738	1,654,738	98.5	224,555	224,550	26.3	339,867
District of Columbia	949,496	393,222	393,222	3.3	471,782	447,752	4.3	145,000	97,862	.9	10,660
Hawaii	926,033				640,809	621,561	8.9				304,472
TOTALS	195,000,000	3,683,151	3,622,308	530.8	96,332,373	93,420,403	6,209.7	46,596,389	44,894,112	4,007.4	53,063,177

CURRENT STATUS OF UNITED STATES WORKS PROGRAM GRADE CROSSING PROJECTS

(AS PROVIDED BY THE EMERGENCY RELIEF APPROPRIATION ACT OF 1935)

AS OF APRIL 30, 1936

STATE	APPORTIONMENT	COMPLETED				UNDER CONSTRUCTION				APPROVED FOR CONSTRUCTION				BALANCE OF FUNDS AVAILABLE FOR NEW PROJECTS
		Estimated Total Cost	Works Program Funds	Eliminated by Separation or Relocation	Protected By Signals or Otherwise	Estimated Total Cost	Works Program Funds	Eliminated by Separation or Relocation	Protected By Signals or Otherwise	Estimated Total Cost	Works Program Funds	Eliminated by Separation or Relocation	Protected By Signals or Otherwise	
Alabama	$4,034,617	$9,124	$9,124	1		$2,276,607	$2,276,607	24		$1,473,819	$1,473,819	12	5	$275,067
Arizona	1,256,099	47,412	47,412	1		814,319	664,815	8		158,526	158,526	1		385,346
Arkansas	3,574,060					1,057,577	1,053,890	23		1,179,707	1,177,877	22		1,342,294
California	7,486,362					6,018,361	5,774,181	35		385,220	384,122	4		1,328,059
Colorado	2,631,567					1,116,543	1,095,543	18		150,000	150,000	2		1,386,024
Connecticut	1,712,684													1,712,684
Delaware	418,239													418,239
Florida	2,827,883					1,424,039	1,421,728	13		277,906	277,906	2		1,128,248
Georgia	4,895,949					10,581	10,581			344,859	344,859	5		4,540,510
Idaho	1,674,479	7,303	7,000	1		852,091	852,091	12						822,388
Illinois	10,307,184					2,299,648	2,295,648	24		3,758,231	3,758,231	32		4,253,305
Indiana	5,111,096					1,996,918	1,996,918	17		1,515,168	1,515,168	5		1,599,010
Iowa	5,600,679					1,518,955	1,451,000	30		1,220,745	1,164,500	29		2,978,179
Kansas	5,246,258					2,182,819	2,182,819	24		2,773,990	2,773,990	29		289,450
Kentucky	3,672,387					957,612	957,612	12		1,804,573	1,279,545	9	1	1,435,230
Louisiana	3,213,467					48,202	48,202			1,587,938	1,291,651	17		1,873,614
Maine	1,426,861					366,936	366,603	6		295,480	295,480	8		764,779
Maryland	2,061,751					60,000	60,000	1		965,247	942,778	6		1,058,973
Massachusetts	4,210,833					956,239	956,239	6		416,981	416,981	3		2,837,613
Michigan	6,765,197	121,850	121,850	1		4,519,252	4,519,252	36		1,197,200	1,197,200	8		926,895
Minnesota	5,395,441					1,014,882	1,008,832	17		1,194,618	1,194,618	33		3,191,991
Mississippi	3,241,475					1,458,857	1,458,857	29		550,817	550,817	13		1,231,800
Missouri	6,142,153					1,409,308	1,409,308	11		3,348,902	3,348,902	20	8	1,383,942
Montana	2,722,327					2,165,879	2,165,879	34		441,025	441,025	3	1	115,424
Nebraska	3,556,441	40,669	40,669	1		1,502,013	1,502,013	46		622,739	622,739	20		1,431,689
Nevada	887,260					278,735	278,735	6		388,882	388,882	3		178,974
New Hampshire	822,484					207,624	207,624			164,763	164,763	3		450,097
New Jersey	3,983,826	136,191	136,191	3		685,340	685,340	4		367,714	367,714	1		2,930,771
New Mexico	1,725,286					378,820	378,820	5		559,674	547,503	1		662,773
New York	13,577,189					5,859,232	5,597,586	19		2,549,670	2,549,390	5		5,430,213
North Carolina	4,823,958	10,268	10,268			1,132,832	1,132,832	13		475,497	475,497	7		3,205,360
North Dakota	3,207,473					201,184	201,184	5		440,764	440,764	17		2,565,525
Ohio	8,439,897					206,498	206,498	1		828,050	818,050	7		7,415,349
Oklahoma	5,004,711					1,156,729	1,156,729	23		1,263,250	1,258,250	19		2,589,731
Oregon	2,334,204					920,425	919,886	10		1,438,537	1,314,364	9		99,954
Pennsylvania	11,483,613					912,186	880,819	16		2,502,462	2,482,596	21		8,120,198
Rhode Island	699,691					665,505	635,386	4						64,305
South Carolina	3,059,956					958,685	954,232	20		244,723	244,723	5		1,861,001
South Dakota	3,249,086					531,697	531,697	12		317,092	317,092	9		2,348,523
Tennessee	3,903,979	51,774	51,774	1		366,701	365,701	9		248,032	248,032	4		3,290,246
Texas	10,855,982	34,420	34,420	2		3,163,714	3,042,357	41		3,246,266	2,845,758	32	7	4,933,448
Utah	1,230,763					392,410	392,410	4		246,951	234,897	4		603,456
Vermont	729,857					432,826	431,467	5		75,066	75,066	4		223,323
Virginia	3,774,287					550,432	489,103	11		934,089	934,089	30	7	2,351,095
Washington	3,095,041					1,722,370	1,717,570	19	1	178,600	178,569	4		1,198,902
West Virginia	2,677,937	55,366	55,365	2		2,345,175	2,336,297	20		387,238	387,238	2		2,290,699
Wisconsin	5,022,683					112,085	112,085	7		635,807	635,807	7		2,050,579
Wyoming	1,360,841					166,697	166,697	2		102,599	102,598	1		1,090,795
District of Columbia	410,804					296,218	295,333	3		253,264	238,616	1		5,491
Hawaii	453,703													158,370
TOTALS	196,000,000	514,377	514,073	13		59,666,758	58,645,006	679	1	43,525,949	42,010,992	479	29	94,829,929

PUBLICATIONS of the BUREAU OF PUBLIC ROADS

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D.C. As his office is not connected with the Department and as the Department does not sell publications, please send no remittance to the United States Department of Agriculture.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1924. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1927. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1928. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1929. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1933. 5 cents.

Report of the Chief of the Bureau of Public Roads, 1934. 10 cents.

Report of the Chief of the Bureau of Public Roads, 1935. 5 cents.

DEPARTMENT BULLETINS

No. 347D . . Methods for the Determination of the Physical Properties of Road-Building Rock. 10 cents.

No. 583D . . Reports on Experimental Convict Road Camp. Fulton County, Ga. 25 cents.

No. 1279D . . Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.

TECHNICAL BULLETINS

No. 55T . . Highway Bridge Surveys. 20 cents.

No. 265T . . Electrical Equipment on Movable Bridges. 35 cents.

MISCELLANEOUS PUBLICATIONS

No. 76MP . . The Results of Physical Tests of Road-Building Rock. 25 cents.

Federal Legislation and Regulations Relating to Highway Construction. 10 cents.

Supplement No. 1 to Federal Legislation and Regulations Relating to Highway Construction.

No. 191 . . . . Roadside Improvement. 10 cents.

The Taxation of Motor Vehicles in 1932. 35 cents.

An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.

Single copies of the following publications may be obtained from the Bureau of Public Roads upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS CIRCULARS

No. 62MC . . Standards Governing Plans, Specifications, Contract Forms, and Estimates for Federal-Aid Highway Projects.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).

Report of a Survey of Transportation on the State Highways of Vermont (1927).

Report of a Survey of Transportation on the State Highways of New Hampshire (1927).

Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).

Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).

Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U. S. Bureau of Public Roads, Willard Building, Washington, D. C.

CURRENT STATUS OF UNITED STATES PUBLIC WORKS ROAD CONSTRUCTION

AS PROVIDED BY SECTION 204 OF THE NATIONAL INDUSTRIAL RECOVERY ACT (1934 FUNDS) AND BY THE ACT OF JUNE 18, 1934 (1935 FUNDS)

AS OF APRIL 30, 1936

STATE	APPORTIONMENTS Sec. 204 of the Act of June 16, 1933 (1934 Fund)	APPORTIONMENTS Act of June 18, 1934 (1935 Fund)	COMPLETED Total Cost	COMPLETED 1934 Public Works Funds	COMPLETED 1935 Public Works Funds	COMPLETED Mileage	UNDER CONSTRUCTION Estimated Total Cost	UNDER CONSTRUCTION 1934 Public Works Funds	UNDER CONSTRUCTION 1935 Public Works Funds	UNDER CONSTRUCTION Mileage	APPROVED 1934 Public Works Funds	APPROVED 1935 Public Works Funds	APPROVED Mileage	BALANCE 1934 Public Works Funds	BALANCE 1935 Public Works Funds
Alabama	$8,370,133	$4,259,842	$14,351,696	$8,174,408	$2,819,061	736.4	$1,072,225	$160,296	$911,929	38.5		$475,248	3.0	$35,429	$53,604
Arizona	5,211,960	2,641,935	8,702,843	5,203,929	2,393,040	540.6	289,662		200,270	5.6	$21,152	28		8,051	48,597
Arkansas	6,748,335	3,428,049	10,430,415	6,563,258	2,900,773	596.9	510,692	63,188	427,196	20.9		48,548	2.1	100,737	51,531
California	15,607,354	7,932,206	28,200,431	15,590,557	6,639,585	740.2	2,357,572		1,232,628	20.2				16,797	59,173
Colorado	6,874,530	3,486,006	11,125,872	6,831,431	3,441,533	636.3	6,817		6,500					43,099	38,172
Connecticut	2,865,740	1,454,868	4,061,007	2,790,583	857,758	69.3	411,623		396,103	3.8		820	.9	75,157	171,008
Delaware	1,819,088	923,395	2,643,857	1,819,088	782,660	128.3	32,528		32,528	20.8		108,207	1.6		112,565
Florida	5,231,834	2,661,343	8,285,940	5,188,399	1,889,808	288.6	706,372		643,015			15,955	.8	43,435	112,565
Georgia	10,091,185	5,113,491	11,807,849	9,085,816	2,276,297	674.4	1,549,860	458,333	1,043,504	72.9	357,556	632,826	56.4	289,481	1,160,864
Idaho	4,486,249	2,277,486	6,398,877	4,402,467	1,583,190	489.4	634,861	1,685,292	633,081	12.1	59,759	27,947	4.6	24,023	61,215
Illinois	17,570,770	8,921,401	21,855,736	15,777,697	5,449,114	612.7	4,932,117	196,028	3,144,413	82.1	3,837	210,914		103,944	299,927
Indiana	10,037,843	5,088,965	13,204,271	9,649,030	2,965,002	400.8	2,107,017		1,876,486	85.1	192,785				36,560
Iowa	10,055,660	5,118,361	15,206,714	9,941,506	4,683,028	1,214.2	297,801	114,154	162,100	4.8	68,553	245,741	5.0	15,589	27,491
Kansas	10,089,604	5,117,675	14,710,316	9,966,308	4,361,660	1,110.8	756,595	39,153	717,242	21.4	29,243	5,140	2.2	5,140	33,653
Kentucky	7,517,359	3,818,311	10,662,755	6,976,085	2,915,989	760.6	1,149,356	463,762	612,448	45.3		177,476	5.8	48,269	112,398
Louisiana	5,828,591	2,963,932	7,951,371	5,147,521	2,184,476	215.8	1,127,889	608,584	519,305	34.8	53,784	72,999	6.4	18,702	187,151
Maine	3,369,917	1,711,586	7,097,525	3,340,131	1,543,197	191.7	108,297		108,283	1.4				29,786	60,107
Maryland	3,564,527	1,810,058	4,470,983	2,899,421	624,669	114.5	1,035,926	552,686	471,388	33.8	30,000	268,085	11.8	82,420	445,916
Massachusetts	6,597,100	3,350,474	7,112,257	4,601,909	1,853,329	104.3	3,071,060	1,896,850	1,174,210	11.0	11,228	2,247	.1	98,341	290,688
Michigan	12,736,227	6,462,568	18,329,024	12,538,746	4,593,335	675.9	2,018,575	163,400	1,797,198	92.1		30,825		34,081	31,211
Minnesota	10,656,569	5,425,551	15,432,903	9,867,696	4,755,179	1,627.3	838,712	646,206	181,274	19.5		203,936	1.8	131,439	285,162
Mississippi	6,978,675	3,540,227	11,226,383	6,360,117	2,024,248	650.8	1,844,969	495,536	1,267,522	86.0	6,555	206,106	12.2	96,467	42,350
Missouri	12,180,306	6,173,740	15,328,284	10,915,101	3,466,956	1,067.0	4,165,561	1,162,219	2,614,187	84.4		92,597	2.4	102,986	
Montana	7,439,748	3,769,734	11,006,151	7,178,165	3,165,014	1,005.3	614,655	159,462	445,063	24.8	57,745	127,440	22.9	44,206	22,257
Nebraska	7,828,961	3,964,364	12,377,511	7,730,371	3,377,810	992.1	814,821	65,535	539,199	43.0		37,959	8.2	33,055	9,396
Nevada	4,545,917	2,302,336	6,753,604	4,484,176	1,988,495	741.9	298,776	26,150	272,626	11.9		5,250		35,591	35,985
New Hampshire	1,909,839	969,462	2,940,544	1,904,950	904,559	77.2	33,288		33,026	.5				4,889	31,877
New Jersey	6,346,039	3,220,879	6,925,209	5,986,387	580,690	76.6	2,644,014	175,941	2,151,139	10.7	7,903	303,276	6.6	183,711	185,774
New Mexico	5,792,935	2,941,700	8,506,930	5,624,331	2,667,170	763.5	151,695		151,695	1.1		29,490	.9	160,702	93,346
New York	22,330,101	11,327,921	37,142,994	21,549,629	9,102,488	799.8	3,176,350	553,400	2,073,999	25.2	156,984	107,442	1.4	70,088	43,992
North Carolina	9,522,293	4,840,941	14,251,872	9,041,120	3,994,645	1,321.2	697,561	122,138	558,528	19.9	180,784	205,439	13.5	178,252	82,329
North Dakota	5,804,448	2,938,967	7,240,549	5,447,197	1,136,441	1,949.5	898,447	169,046	670,806	123.0	29,502	570,011	65.9	158,703	561,709
Ohio	15,484,592	7,865,012	22,635,392	15,286,090	5,642,836	751.2	2,245,826	140,461	1,995,496	43.8	11,000	54,370	.6	47,051	172,310
Oklahoma	9,216,798	4,685,180	13,501,958	9,053,666	3,500,710	794.0	937,178	147,071	788,372	10.6	5,126	153,826	1.9	16,060	242,272
Oregon	6,106,896	3,097,814	9,483,883	5,950,972	2,650,162	461.8	434,798	84,475	282,101	6.6		109,293	.8	71,449	56,258
Pennsylvania	18,891,004	9,590,788	27,273,193	17,886,202	8,123,267	981.4	1,791,944	736,539	940,175	77.4		142,764	1.6	263,136	384,581
Rhode Island	1,998,708	1,014,572	2,982,260	1,998,708	850,541	88.0	139,700	32,110	137,982	1.1		190,289	9.0		26,050
South Carolina	5,459,165	2,770,954	7,235,118	5,216,619	1,819,893	584.8	567,261		513,192	30.1	49,682	217,548	24.3	160,755	247,580
South Dakota	6,011,479	3,047,643	8,472,324	5,746,663	2,169,531	1,471.0	577,078	21,968	555,110	60.5	85,146			157,702	105,465
Tennessee	8,492,619	4,302,991	12,319,297	8,205,810	3,216,289	471.7	1,005,960	285,484	624,075	12.4		321,191	9.0	1,325	141,437
Texas	24,244,024	12,291,253	34,988,590	23,375,505	9,978,555	2,716.2	3,295,610	807,494	2,173,760	70.0		79,851	7.1	61,024	59,103
Utah	4,194,708	2,132,691	7,001,517	4,156,356	1,861,919	584.0	330,104	6,060	265,691	6.9				32,291	2,081
Vermont	1,867,573	948,007	3,053,006	1,863,531	844,822	137.6	109,059	3,922	90,573	2.4		4,750	3.0	121	7,562
Virginia	1,416,757	3,765,387	11,187,348	7,148,418	3,103,326	573.0	485,596	112,885	365,260	44.2	55,148	56,483		100,307	240,312
Washington	6,115,867	3,106,412	8,811,334	6,098,252	2,489,651	292.9	574,946		568,849	10.1		2,387		17,615	45,525
West Virginia	4,474,234	2,280,335	5,523,975	4,312,210	1,005,360	186.7	1,042,371	112,719	875,285	31.7		293,744	4.2	49,305	105,946
Wisconsin	9,724,881	4,941,837	14,746,871	9,697,528	4,261,880	604.3	582,225	7,300	532,483	15.4		110,182		20,053	37,292
Wyoming	4,501,327	2,287,712	6,672,426	4,433,877	2,057,180	1,008.5	236,611	46,705	163,171	28.8		30,154		20,745	37,207
District of Columbia	1,918,469	973,842	2,569,573	1,909,584	659,854	19.4	298,141	351,635	262,641	2.9				8,885	51,348
Hawaii	1,871,062	949,778	1,885,014	1,510,686		40.0	1,465,742		914,171	15.6				8,740	35,607
TOTALS	394,000,000	200,000,000	574,065,732	376,448,207	148,186,779	33,440.4	56,483,644	12,874,347	39,130,538	1,527.1	1,373,472	6,008,769	296.0	3,303,974	6,673,914